1 # MARKED-UP VERSION OF SUBSTITUTE SPECIFICATION

2 # UNDER 37 C.F.R. 1.125

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4 **Per Zone Variable BPI for Improving Storage Device Capacity and Yield**

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10

11 ## Field of the Invention

12 The present invention relates ~~generally~~ to ~~the storage of~~ information

13 storage on a ~~fixed~~ storage media~~, and more particularly to improving storage of~~

14 ~~information on rotating magnetic media~~ such as a disks in a disk drive.

15

16 ## Background of the Invention

17 Data storage devices such as disk drives are used in many data

18 processing systems ~~for data storage~~. Typically a disk drive includes a magnetic

19 data disk having disk~~recording~~ surfaces with concentric data tracks, and a

20 transducer head paired with each disk~~recording~~ surface~~,~~ for reading data from

21 and writing data to~~, and reading data from,~~ the data tracks. ~~Each paired~~

22 ~~magnetic head and media surface couples to provide a unique data recording~~

23 ~~capability which depends on the fly height of the head from the recording surface,~~

24 ~~the quality/distribution of magnetic media on the recording surface, and the~~

25 ~~magnetic properties of the magnetic head.~~

26

27 Disk drive storage capacity increases by increasing the data density (or

28 areal density) of the data stored on the disk surfaces. Data density is the linear

29 bit density on the tracks multiplied by the track density across the disk surface.

30 Data density is measured in bits per square inch (BPSI), linear bit density is

31 measured in bits per inch (BPI) and track density is measured in tracks per inch

1   (TPI). As data density increases, the head performance distribution also

2   increases which diminishes disk drive storage capacity and yield.

3

4   ~~C~~Conventional disk drives fail to account for ~~methods of recording data~~

5   ~~using the paired head and recording surface are inefficient because they do not~~

6   ~~take into consideration~~ the differen~~t~~ces ~~in data recording~~ capabilities ofbetween

7   the ~~one pair of~~ head and disk~~recording~~ surface pairs~~, and another head and~~

8   ~~surface pair~~. Conventionally, each disk surface is formatted to store the same

9   amount of data as every other disk surface. However, each head and disk

10 surface pair has unique data recording capability, such as sensitivity and

11 accuracy, which depends on the fly height of the head over the disk surface, the

12 magnetic properties of the head and the quality/distribution of the magnetic

13 media for the disk surface. Thus, in conventional disk drives a head and disk

14 surface pair that has a low error rate is formatted to the same BPI and TPI as a

15 head and disk surface pair that has a high error rate.

16

17 _____ ~~Though the heads are designed to perform identically in read/write~~

18 ~~operations, in practice different heads in a disk drive can have different read/write~~

19 ~~performance capabilities. Lower performing heads cannot read/write data as that~~

20 ~~of other heads in the disk drive. Typically, a single error rate level and a single~~

21 ~~storage capacity level are used to record data for all the pair heads and surfaces.~~

22 ~~This results in inefficient data storage for those pairs of heads and surfaces that~~

23 ~~can store more data. It also lowers the qualification yields of the disk drives~~

24 ~~because one or more pairs of heads and surfaces do not record data at the~~

25 ~~qualifying error rate and capacity levels.~~

26

27 ~~Further, in high data rate design of disk drives, as the recording density~~

28 ~~(i.e. bits-per-inch and/or tracks-per-inch) is increased, maintaining transducer~~

29 ~~head tolerances has become a challenge. Variance in the relative head~~

30 ~~performance distribution increases with increasing data density. In conventional~~

1 ~~disk drives, the drive yield and capacity suffers as a result of head performance~~

2 ~~variations in disk drives.~~

3

4 ~~One method of increasing the data storage capacity of a disk drive~~

5 ~~includes increasing the areal density of the data stored on the media surfaces~~

6 ~~(bits/sq. in. -- BPSI). Areal density is the track density which is the number of~~

7 ~~tracks per radial inch (TPI) that can be packed onto the media/recording surface,~~

8 ~~multiplied by the linear density (BPI) which is the number of bits of data that can~~

9 ~~be stored per linear inch.~~

10

11 Conventional <u>disk drive manufacturing</u>~~processes~~ <u>applies a single error</u>

12 <u>rate and a single data storage level for the head and disk surface pairs, and</u> ~~for~~

13 ~~qualifying disk drives~~ <u>scraps</u>~~-a~~ <u>disk drive</u>~~s~~ <u>that include a low performing head and</u>

14 <u>disk surface pair that fails to meet</u> ~~when~~ <u>the qualifying requirements</u>~~measured~~

15 ~~disk capacity of the disk drive is less than a target disk capacity.~~ <u>This lowers</u>

16 <u>storage capacity due to inefficient use of high performing head and disk surface</u>

17 <u>pairs that can store more data, and lowers yield due to disk drives being</u>

18 <u>scrapped if they include a low performing head and disk surface pair even if they</u>

19 <u>also include a high performing head and disk surface pair</u> ~~Conventionally, each~~

20 ~~recording surface is formatted to store the same amount of data as every other~~

21 ~~recording surface. Thus, a recording surface that has a low error rate is~~

22 ~~formatted to the same TPI and BPI levels, as a recording surface having a high~~

23 ~~error rate, even though it can store more data. However, by adopting a single~~

24 ~~TPI and BPI level for every recording surface, conventional processed fail to~~

25 ~~account for the differences in sensitivity and accuracy of the paired head and~~

26 ~~recording surface, which results in less data storage and more waste of space on~~

27 ~~each recording surface. This also results in lower overall yields of disk drives~~

28 ~~because if even a few of the recording surfaces do not meet their targeted~~

29 ~~capacity, the sum of the surface capacities of all the media surfaces will be less~~

30 ~~than the target capacity, causing the entire disk drive to fail.~~

31

1   U.S. Patent Nos. 6,091,559 and 5,596,458 provide ~~for recording at~~

2   different BPI on different disk~~recording~~ surfaces, however these approaches~~,~~

3   ~~such methods~~ do not take into consideration multiple constraints, including head

4   performance across the stroke per disk surface ~~affecting disk drive capacity~~, ~~disk~~

5   ~~drive~~ performance requirements such as ~~(e.g.,~~ throughput~~)~~ and manufacturing

6   requirements such as ~~(e.g.,~~ test time~~)~~. Instead, disk surface z~~Z~~one frequencies

7   are selected based on ~~measurement of~~ a single metric for~~on~~ one head.

8

9   There is, therefore, a need for ~~a method of~~ storing data in a disk drive

10 which improves disk drive storage capacity and yield and ~~while~~ accounts for

11 ~~meeting the desired target drive capacity or increasing the drive capacity while~~

12 ~~meeting a desired drive yield by taking advantage of the~~ head performance

13 variation.

14

15   **Summary of the Invention**

16   The present invention satisfies th~~i~~ese needs~~.~~

17

18   In an embodiment, a variable BPI storage format is a function of ~~storage~~

19 zones in data storage devices, such as disk drives, based on head performance

20 variation between different heads in a set of data storage devices.

21

22   In another embodiment,~~- According to one embodiment of the present~~

23 ~~invention,~~ a population of disk drives is selected, and head performance

24 measurements are taken for ~~each selected disk~~media surface location s at

25 different frequencies. Head p~~P~~erformance distributions ~~are~~ obtained from the

26 head performance measurement s ~~d data,~~ provide storage formats~~and a format~~

27 ~~optimizer uses the distributions to~~ for the disks by determining~~obtain a design of~~

28 different read/write frequencies for~~across~~ the ~~disk~~media ~~surface~~ zones, ~~;~~ and

29 ~~determine head allocation. Once the different frequencies for the zones have~~

30 ~~been determined, then in each disk drive,~~ the heads in each disk drive are

31 assigned to the ~~predetermined~~ frequencies ~~optimized for. As such, the present~~

1 ~~invention allows maintaining consistent performance (both sequential and~~

2 ~~random throughput) across a population of disk drives, and reduced test time.~~

3

4 ~~T~~ ~~This is accomplished by determining head performance and design of~~

5 ~~format at development/design time, and assignment of heads to different~~

6 ~~frequencies at manufacturing time. Therefore, predetermined design of formats~~

7 ~~is performed off-line, and then marries to a manufacturing test process for~~

8 ~~assignment of heads to different frequencies.~~

9

10 ~~In one example, the density/format for each recording surface zone and~~

11 ~~the number of heads allocated to each density, are preselected at design time,~~

12 ~~and at manufacturing time heads are assigned to higher/lower density formats.~~

13 ~~Unlike conventional methods,~~ he head allocation<u>s</u> and assignment<u>s</u> <u>are</u>~~is~~ per

14 head per zone, taking into consideration head performance variation across <u>the</u>

15 zones. <u>For instance</u>~~As such~~, if~~-~~ a first head ~~that~~ performs well at <u>the inner</u>

16 <u>diameter (ID) of the disk</u> but poorly at <u>the outer diameter (OD) of the disk</u>, and a

17 second head has reverse performance, <u>then</u> ~~that performance is traded off~~

18 ~~wherein~~ the first head is assigned <u>a</u> ~~to~~ high <u>BPI</u>~~density~~ at <u>the</u> ID and at low

19 <u>BPI</u>~~density~~ at <u>the</u> OD, and the second head <u>is assigned</u> in the opposite fashion.

20 T<u>In</u>~~the~~ per zone variable BPI <u>storage format</u> ~~for~~ improv<u>es</u>~~ing~~ storage capacity <u>by</u>

21 <u>taking</u> ~~according to the present invention,~~ several manufacturing and customer

22 constraints ~~are taken~~ into consideration. Performance of each head across the

23 stroke <u>of the disk surface</u>, as well <u>as</u> performance variation from one head to

24 another, ~~is~~ <u>determines</u> ~~utilized in designing~~ the <u>storage</u>~~density~~ format and

25 ~~assignments of~~ <u>the</u> head <u>assignments</u>~~s to the density formats~~.

26

27 <u>In another embodiment, the head performance and the storage format are</u>

28 <u>determined off-line at development/design time, and then the heads are assigned</u>

29 <u>to the different frequencies at manufacturing time. For</u>~~In one~~ <u>example, the</u>

30 <u>storage format for each</u> ~~disk surface~~ <u>zone and the number of heads allocated to</u>

1   each data density are preselected at design time, and then the heads are

2   assigned to high/low data density storage formats at manufacturing time.

3

4   ——————The present invention provides a variable BPI storage format as a function

5   of storage zones in storage devices, such as disk drives, based on transducer

6   head performance variations between different heads in a set of disk drives.

7   _____In another embodiment, aThe present invention provides a method of

8   definesing thesuch a storage format in multiple data storage devices, with each

9   data storage device having a multipleplurality of storage media and a plurality of

10 corresponding data transducer heads, each transducer head for recording on

11 and playback of information from a corresponding storage mediamedium in

12 multiple zones, and wherein each zone includinges a plurality of concentric

13 tracks for recording on and playback of information. The method includes the

14 steps of: (1) selecting a plurality of a sample of thesaid data storage devices, (2)

15 for each selected data storage device, measuring a record/playback performance

16 capability of each head at one or more read/write frequencies per zone, (3)

17 based on said performance capability measurements, generating head

18 performancestorage density distributions corresponding to at least a number of

19 the heads in said selected data storage devicesbased on the head performance

20 measurements, (4) selecting a group of read/write frequencies for thesaid

21 multiple data storage devices, two or more frequencies for each zone, based on

22 thesaid head performancestorage density distributions, and thereafter, during

23 manufacturing, (5) assigning one of thesaid read/write frequencies to each head

24 based on the performance capability of that head per storage device.

25

26 Advantageously, the present invention provides consistent performance

27 (both sequential and random throughput) across a population of disk drives,

28 improves storage capacity and yield and reduces test time.

29

30

31 **Brief Description of the Drawings**

1   These and other features, aspects and advantages of the present

2 invention will become understood with reference to the following description,

3 appended claims and accompanying figures where:

4   FIG. 1A shows an ~~example partial schematic diagram of a~~ disk drive with

5 an ~~example~~ data storage format ~~according to the present invention~~;

6   FIG. 1B shows ~~another example schematic of~~ drive~~the disk drive of FIG.~~

7 ~~1A illustrating disk drive~~ electronics for the disk drive;

8   FIG. 1C shows a servo tracks and data tracks on a disk ~~n example~~ surface

9 ~~format for data storage according to the present invention~~;

10   FIG. 1D shows an ~~example diagram representing the general~~ zone

11 format~~layout~~ in~~of~~ the~~a~~ disk drive with N disks, ~~and~~ 2N heads, and depicting

12 different heads in ~~a section of~~ a zone on different disk surfaces;

13   FIG. 1E shows another ~~example of capacity~~ zone format~~layout~~ on a disk

14 surface ~~a disk~~;

15   FIG. 1F shows ~~example of a series of radial~~ zones on a disk surface that,

16 ~~wherein~~ each ~~zone~~ includes ~~multiple~~ virtual cylinders;

17   FIG. 1G shows an ~~example representative~~ data track format~~layout~~ for the

18 ~~each of several~~ virtual cylinders in a zone on different disk surfaces with

19 corresponding heads;

20   FIG. 1H shows a ~~nother example~~ servo track and data track format~~layout~~

21 for a zone on different disk surfaces with corresponding heads in which ~~wherein~~

22 the number of servo tracks and data tracks in different virtual cylinders of a zone

23 on different disk surfaces are the same;

24   FIG. 1I shows another ~~example layout wherein the~~ servo and data track

25 format~~layout~~ that varies from zone to zone on a disk surface;

26   FIG. 2A shows an ~~example~~ function and flow/~~functional~~ diagram for~~of~~

27 ~~embodiment of steps of~~ generating the format~~layout~~ of FIG. 1~~1~~1A ~~according to~~

28 ~~the present invention~~;

29   FIG. 2B shows a graph of playback error measurement for a head at a

30 zone at different recording frequencies;

31 ~~FIG. 2C shows an example joint BPI distribution plot;~~

1   FIG. 2C~~D~~ shows ~~an example~~ histogram of the frequency capabilities of the

2   heads in a set of disk drives at a zone at a fixed target error rate;

3   _____FIG. 2D shows a joint BPI distribution;_

4   FIG. 3 shows ~~an example~~ flowchart ~~of an embodiment of steps~~ of

5   vertical~~ariable~~ zoning data collection ~~process~~ in~~of~~ FIG. 2A;

6   FIG. 4 shows ~~an example~~ flowchart of ~~an embodiment of steps of~~ vertical

7   zoning ~~post-measurement processing~~ and per zone joint BPI distribution

8   extraction ~~process~~ in~~of~~ FIG. 2A;

9   FIG. 5 shows ~~an example~~ flowchart of head~~an embodiment of steps of~~

10   ~~vertical zone~~ _assignments_ in ~~process of~~ FIG. 2A; and

11   FIG. 6 shows ~~an example~~ flowchart of ~~an embodiment of steps of~~ format

12   generation and optimization ~~interaction process of~~ in FIG. 2A.

13

14   **Detailed Description of the Invention**

15   Data storage devices used to store data for computer systems include, for

16   example, ~~hard~~ disk drives, floppy ~~disk~~ drives, tape drives, optical and magneto-

17   optical drives~~,~~ and compact ~~disk~~ drives. Although the present invention is

18   illustrated by way of a_n ~~exemplary magnetic hard~~ disk drive ~~100~~, the present

19   invention can be used in other data storage devices and other storage media ~~and~~

20   ~~drives~~, including non-magnetic storage media, is_ as apparent to those~~one~~ of

21   ordinary skill in the art and without deviating from the scope of the present

22   invention.

23

24   ~~Referring to~~ FIGs. 1A-1C show~~,~~ ~~an exemplary~~ hard disk drive 100 ~~is~~

25   diagrammatically depicted for storing user data and/or operating instructions for a

26   host computer ~~system~~ 54. The ~~hard~~ disk drive 100 includes~~comprises~~ an electro-

27   mechanical head-disk assembly 10 that ~~shown in FIG. 1A as~~ includ_es~~ing~~ one or

28   more rotating data storage disks 12 mounted in a stacked, spaced-apart

29   relationship upon a ~~rotating~~ spindle 13~~. The spindle 13 is~~ rotated by a spindle

30   motor 14 at a predetermined angular velocity.

31

1   Each disk 12 includes~~defines~~ at least one disk~~media~~ surface 23, and

2   usually two disk~~media~~ surfaces 23 on opposing sides~~ of each disk 12~~. Each

3   disk~~media~~ surface 23 has associated ~~is coated is coated with~~ magnetic ~~or other~~

4   media for recording data. The spindle ~~drive~~ motor 14 rotate~~turns~~ the spindle 13

5   ~~in order~~ to move the disks 12 past the magnetic transducer heads 16 suspended

6   by the suspension arms 17 over each disk~~media~~ surface 23. Generally, each

7   ~~magnetic~~ head 16 is attached to a~~the~~ suspension arm 17 by a head gimbal

8   assembly (not shown) that enables the ~~magnetic~~ head 16 to swivel to conform to

9   a~~the~~ disk~~media~~ surface 23~~s on the disks 12~~. The suspension arms 17 extend

10   radially from a rotary voice coil motor 20~~actuator (not shown)~~. The voice coil ~~An~~

11   ~~actuator~~ motor 20~~54~~ rotates the suspension ~~actuator and head~~ arms 17 and

12   thereby positions the ~~magnetic~~ heads 16 over the appropriate areas of the

13   disk~~media~~ surfaces 23 in order to ~~locate and~~ read from or write ~~data from or~~ to

14   the disk~~storage~~ surfaces 23. ~~-~~ Because the disks 12 rotate at relatively high

15   speed, the ~~magnetic~~ heads 16 ride over the disk~~media~~ surfaces 23 on a cushion

16   of air (air bearing).

17

18   ~~-~~Each ~~magnetic~~ head 16 includ~~compris~~es a read element (not shown) for

19   reading ~~magnetic~~ data from ~~on~~ a disk ~~magnetic storage media~~ surfaces 23 and a

20   write element (not shown) for writing data to a disk~~on the media~~ surfaces 23.

21   Most preferably, the read element is a magneto-resistive or giant magneto-

22   resistive sensor and ~~although not necessarily,~~ the write element is inductive and

23   has ~~an electrical~~ writ~~e~~ing width which is wider than ~~an electrical~~ reading width of

24   the read element~~, which is preferably of magnetoresistive or giant~~

25   ~~magnetoresistive material~~.

26

27   ~~E~~Referring to FIG. 1C, each disk~~media~~ surface 23 is divided into a

28   ~~plurality of~~ concentric circular data tracks 30 that each have individually

29   addressable data sector~~portions~~ 35~~, such as sectors,~~ in which user data is stored

30   in the form of magnetic bits. The data sectors 35 are separated by narrow

31   embedded ~~narrow~~ servo sectors ~~or spokes~~ 25 arranged in radially extending

1 <u>servo spokes. The servo sectors 25</u> ~~which~~ include a series of phase-coherent

2 digital fields followed by a series of constant frequency servo bursts. The servo

3 bursts are radially offset and circumferrentially sequential, and are provided in

4 sufficient numbers ~~such~~ that fractional amplitude <u>read</u> signals <u>generated</u> ~~picked~~

5 ~~up~~ by the <u>head 16</u>~~read element~~ from portions of at least two <u>servo</u> bursts passing

6 under the <u>head 16</u>~~read element~~ enable the controller 57 to determine and

7 maintain proper ~~head~~ position <u>of the head 16</u> relative to a data track 30. A<u>One</u>

8 ~~example of a~~ servo burst pattern for use with <u>a head that includes</u> ~~an inductive~~

9 ~~write element~~<u>a /</u>magneto-resistive read element <u>and an inductive write element</u>

10 ~~head 16~~ is <u>describe</u>~~provide~~d by commonly assigned U.S. Patent No<u>.</u> 5,587,850~~,~~

11 entitled<u>:</u> "Data Track Pattern Including Embedded Servo Sectors for Magneto-

12 Resistive Read/Inductive Write Head Structure for a Disk Drive"~~,~~ <u>which is</u>

13 incorporated herein by reference.

14

15   The ~~drive~~ controller 57 controls ~~operation of~~ the ~~pairs of magnetic~~ heads

16 16 ~~and media surfaces 23~~ to read <u>from</u> and write ~~data onto~~ <u>to</u> the <u>each</u> diskmedia

17 surface<u>s</u> 23. The ~~drive~~ controller 57 preferably <u>is</u>~~comprises~~ an application

18 specific integrated circuit<u>s chip (ASIC)</u> ~~chip~~ which is connected by a printed

19 circuit board 50 <u>to</u> ~~with~~ other <u>ASIC</u>~~chips~~, such as a read/write channel ~~chip~~ 51, a

20 motor<u>s</u> drive<u>r</u> ~~chip~~ 53~~,~~ and a cache buffer ~~chip~~ 55~~, into an electronic circuit as~~

21 ~~shown in FIG. 1B~~. The controller 57 preferably includes an interface 59 which

22 connects to the host computer 54 via a known bus ~~structure~~ 52~~,~~ such as <u>an</u> ATA

23 or SCSI <u>bus</u>.

24

25   The controller 57 executes embedded or system software

26 <u>includ</u>~~comprising~~ing programming code that monitors and operates the <u>disk drive</u>

27 <u>100</u>~~controller system and driver 100~~. During a read or <u>write</u>~~data retrieval~~

28 operation, the <u>host</u> computer ~~system~~ 54 determine<u>s</u>~~d~~ the <u>"</u>address<u>"</u> where the

29 data is located <u>i</u>~~o~~n the disk drive 100<u>. The address specifies the</u> ~~, i.e., magnetic~~

30 head <u>16</u>~~number~~, the <u>data</u> track 30~~,~~ and the <u>data sector</u>~~relevant portion(s)~~ 35 ~~of~~

31 ~~the track 30~~. This data is transferred to the ~~drive~~ controller 57 which maps the

1   address to the physical location in the disk drive 100, and in response to reading

2   the servo information in the servo sectors 25, operates the voice coil actuator

3   motor 2054 and suspension arm 17 to position thea magnetic head 16 over the

4   corresponding data track 30. As the diskmedia surface 23 rotates, the magnetic

5   head 16 reads the servo information embedded in each servo sectorspoke 25

6   and also reads an address of each data sectorportion 35 in the data track 30.

7

8   During a read operation, wWhen the identified data sectorportion 35

9   appears under the magnetic head 16, the entire contents of the data

10   sectorportion 35 containing the desired data isare read. In reading data from the

11   diskmedia surface 23, the head 16read element (not shown) senses a variation

12   in an electrical current flowing through a magnetoresistive sensor of the read

13   element (not shown) when it passes over an area of flux reversals on the disk

14   surface 23 of the media. The flux reversals are transformed into recovered data

15   by the read/write channel chip 51 in accordance with a channel algorithm such as

16   partial response, maximum likelihood (PRML). The recovered data is then read

17   into the cache buffermemory chip 55 of the disk drive 100 from wherence it is

18   transferred to the host computer system 54. The read/write channel 51 most

19   preferably includes a quality monitor function which enables measuresment of

20   the quality of recovered data and thereby provides an indication of the data error

21   rate. One channel implementation which employs channel error metrics is

22   described in commonly assigned U.S. Patent No., 5,521,945 to Knudson,

23   entitled: "Reduced Complexity EPR4 Post-Processor for Sampled Data

24   Detection" which is, incorporated herein by reference. The present inventioni

25   uses the indication of recovered data error to is used in order to select linear

26   bitdata density, track density and/or error correction code levels, in accordance

27   with principles of the present invention, as more fully explained hereinbelow.

28

29   Writing or storing data on the media surface 23 is the reverse of the

30   process for reading data. During a write operation, the host computer system 54

31   remembers the addresses for each file on the diskmedia surface 23 and which

1   data sector~~portions~~ 35 are available for new data. The ~~drive~~ controller 57

2   operates the voice coil ~~actuator~~ motor 20~~54~~ in response to the servo information

3   read back from the ~~embedded~~ servo sectors 25 ~~in order~~ to position the head 16a

4   ~~magnetic Head1~~, settles the head 16 into a writing position, and waits for the

5   appropriate data sector~~portions~~ 35 to rotate under the head 16 to ~~perform the~~

6   ~~actual~~ writ~~e~~ing the~~of~~ data. To write data on the disk~~media~~ surface 23, an

7   electrical current is passed through a write coil in the inductive write element ~~(not~~

8   ~~shown)~~ of the head 16 to create a magnetic field across a magnetic gap in a pair

9   of write poles that magnetizes the ~~magnetic storage media coating the~~ disk~~media~~

10 surface 23 under the head 16. When the data track 30 is full, the ~~drive~~ controller

11 57 moves the ~~magnetic~~ head 16 to the next available data track 30 with sufficient

12 contiguous space for writing ~~of~~ data. If still more track capacity is required,

13 another head 16 is used to write data to a data sector~~portion~~ 35 of another data

14 track 30 on another disk~~media~~ surface 23.

15

16   T~~In one aspect,~~ the present invention increases the ~~data~~ storage capacity

17 and yield of data storage devices, such as the disk drive 100, ~~having a plurality~~

18 ~~of~~ magnetic media surfaces, such as the disk surfaces 23~~, such as hard disk~~

19 ~~drive 100 including disks 12 covered with magnetic media~~.

20

21 V~~Overview of general method~~ vertical Z~~z~~oning

22   In every disk drive, there is a distribution associated with the head and

23 disk surface /~~media~~ pair performance ~~in that disk drive~~. ~~-~~The present invention

24 takes advantage of that distribution to determine different linear bit density (BPI)

25 recording frequency assignments for the heads, and optionally track allocation.

26

27   A ~~According to one embodiment of the present invention, a~~ set of disk

28 drives is selected, and head performance measurements are taken for each

29 selected disk~~media~~ surface location in the disk drives at different frequencies.

30

1 ————Empirical frequency capability histograms are extracted at a ~~given known~~

2 target performance metric from the measurement data. Head performance

3 distributions ~~Probability cumulative distribution functions~~ (such as joint BPI

4 ~~probability~~ distributions) are estimated from the histograms and fed into a format

5 optimizer to obtain and design ~~(vertically zoned)~~ frequency format profiles ~~(i.e.,~~

6 across the stroke and the disk~~media~~ surface ~~zones)~~ as well as the optimal

7 number of head allocations to the frequencies. _Once the frequency format

8 profiles and the optimal number of head allocations are ~~designed and pre-~~

9 determined, during a test process, every head at every zone is assigned to one

10 of the ~~multiple pre-determined~~ frequencies based on the head's performance

11 ~~capability.~~

12

13 ———— ~~As such, the present invention allows maintaining consistent performance~~

14 ~~(sequential/random throughput) across several of disk drives, without introducing~~

15 ~~significant additional test time. This is accomplished by determining head~~

16 ~~performance and design of format at development/design time, and assignment~~

17 ~~of heads to different frequencies at manufacturing time. Therefore, the~~

18 ~~predetermined design of frequency format profiles and (optimal) number of head~~

19 ~~allocations are performed off-line while the assignment of heads to different~~

20 ~~frequencies is performed during the test process such as during manufacturing.~~

21

22 ———— ~~Unlike conventional methods, in the present invention head allocation and~~

23 ~~assignment is per-head per-zone, taking into consideration head performance~~

24 ~~variation across zones (i.e. across the stroke). As such, during head frequency~~

25 ~~assignment, if a first head performs well at ID but poorly at OD, and a second~~

26 ~~head has the opposite performance, the performance variation between the~~

27 ~~heads is traded off such that the first head is assigned to high-density (frequency)~~

28 ~~at ID and at low-density at OD, and the second head is assigned to low-density at~~

29 ~~ID and high-density at OD. In a method of per-zone variable bits-per-inch (BPI or~~

30 ~~linear density) for improving capacity according to the present invention, several~~

31 ~~manufacturing and customer constraints are taken into consideration. And,~~

1 ~~performance of each head across the stroke, as well performance variation from~~

2 ~~one head to another, is utilized in designing the density format and assignments~~

3 ~~of heads to the density formats.~~

4

5 ——— ~~Referring back to~~ FIG. 1A shows~~,~~ a storage format for the disk drive

6 100. Each disk surface 23 includes zones 60 that extend from one radius of the

7 disk 12 to another radius of the disk 12, and the format of the zones 60 on each

8 disk surface 23 is the same. The~~n example of density layout according to an~~

9 ~~embodiment of the present invention is shown. In one aspect, the present~~

10 ~~invention provides a~~ variable BPI storage format is ~~layout as~~ a function of the

11 zones 60 on each disk surface 23 based ~~on e.g.~~ two data recording formats --

12 ~~(i.e., low~~ high data density and ~~high~~ low data density -- ~~)~~ that u~~tilize:~~se (1) head

13 performance variation from one head 16 to the next head 16 in the disk drive

14 100, and (2) the performance ~~(variation)~~ of a given head 16 across the stroke of~~n~~

15 a disk surface 23. ~~Further, the present invention provides a method of~~

16 ~~generating said layout.~~

17

18

19 ——— ~~In this example, each zone comprises a group of tracks laid out in zones~~

20 ~~60 between one radius and another radius on the disk surface 23, wherein the~~

21 ~~zone layout for the multiple disk surfaces in each disk drive 100 are the same.~~

22 ——— The~~A~~ disk drive 100 includes the ~~N~~ disks 12 depicted as ~~(d~~Disks~~ 1

23 ~~to~~hrough ~~Disk~~N, the heads 16 depicted as heads 1 to 2N, and the disk surfaces

24 23 depicted as disk surfaces 1 to 2N. E~~),~~ each disk 12 includes~~having~~ two

25 opposing disk surfaces 23, and each head 16 is associated with one of the disk

26 surfaces 23~~a Surface1 and opposing Surface.~~ For instance, head 1 is

27 associated with disk surface 1 of disk 1, head 2 is associated with disk surface 2

28 of disk 1, head 3 is associated with disk surface 3 of disk 2, and head 2N is

29 associated with disk surface 2N of disk N.

30

1   ~~E2, wherein~~ each disk surface 23 includes the zones 60 depicted as ~~has~~

2   ~~M zones (z~~Zones 1 ~~throug~~oh ~~ZoneM)~~ across its ~~the actuator~~ stroke, ~~with,~~ ~~and~~

3   ~~one head per disk surface. For each disk surface,~~ ~~z~~Zone 1 ~~is~~ at the ~~in~~ID and ~~z,~~

4   Zone M ~~is~~ at the ~~in~~OD. ~~T, wherein~~ the radial boundaries o~~n~~f ~~z~~Zone 1 of disk

5   ~~s~~Surface 1 of ~~d~~Disk 1 are the same as the radial boundaries of ~~z~~Zone 1 o~~n~~f disk

6   ~~s~~Surface 2 of ~~d~~Disk 1, and so on. Similarly, the radial boundaries of ~~z~~Zone M on

7   disk ~~s~~Surface 1 of ~~d~~Disk 1 are the same as the radial boundaries of ~~z~~Zone M on

8   disk ~~s~~Surface 2 of ~~d~~Disk 1, and so on. However, different zones 60 across the

9   stroke on each disk surface 23 need not necessarily have the same number of

10   data tracks 30 or TPI ~~(e.g., Zone1 and ZoneM on the same surface do not~~

11   ~~necessarily have the same number of tracks).~~ For example, ~~z~~Zone 1 on disk

12   ~~s~~Surface 1 of ~~d~~Disk 1 ~~(i.e., Head1)~~ has the same number of data tracks 30 and

13   the same radial~~physical zone~~ boundaries as ~~z~~Zone 1 on disk ~~s~~Surface 1 of ~~d~~Disk

14   N ~~(Head 2xN), etc.~~ ~~a~~And, ~~z~~Zone M on disk ~~s~~Surface 1 of ~~d~~Disk 1 ~~(Head1)~~ has

15   the same number of data tracks 30 and the same radial~~physical zone~~

16   boundarie~~s~~y as ~~z~~Zone M on disk ~~s~~Surface 1 of ~~d~~Disk N ~~(Head2N)~~. However, the

17   number of data tracks 30 in ~~z~~Zones 1 and ~~ZoneM~~ can be different.

18

19   Each disk surface 23 also includes virtual cylinders 39 depicted as virtual

20   cylinders 1 to n. Each zone 60 includes multiple virtual cylinders 39, and each

21   virtual cylinder 39 includes multiple data tracks 30 on each disk surface 23. ~~The~~

22   ~~physical zone boundaries vertically align on the disks in each disk drive, forming~~

23   ~~virtual cylinders 39 (VC). In this example, there are n virtual cylinders 39, VC1~~

24   ~~through VCn.~~ Further, w~~W~~ithin a virtual cylinder 39, different heads 16 may read

25   and ~~/~~write at different frequencies ~~(e.g.,~~ variable BPI) to provide, ~~hence the~~

26   ~~concept of~~ vertical zoning.

27

28   ~~The level of track density (TPI) can be one of fixed number of preselected~~

29   ~~levels or can be derived from an algorithm that is based on the location of a~~

30   ~~portion 35 of the media surface 23. Embedded servo sectors 25 are initially~~

31   ~~written on a media surface 23 during a factory servo-writing process at a servo~~

1 ~~track density that can be higher than the data track density, as illustrated in FIG.~~

2 ~~1C. Servo bursts within each servo sector 25 are provided in such number and~~

3 ~~placement to enable accurate positioning of the magnetic head 16 in a full range~~

4 ~~of positions across the media surface 23, given the particular effective width and~~

5 ~~characteristics of the read element of a particular head (the read element width~~

6 ~~typically being narrower then the writer carry out the head positioning method,~~

7 ~~information in the embedded servo sector 25 is read by the magnetic head 16~~

8 ~~and passed to the drive controller 57 which directs the actuator motor 20 to~~

9 ~~readjust the position the suspension arm 16. In the example shown in~~ FIG. 1C

10 shows, the data tracks 30 and the servo tracks 37 on the disk surface 23. The

11 data tracks 30 include the data sectors 35, and the servo tracks 37 include the

12 servo sectors 25. ~~the servo track density is about 150% of the maximum~~

13 ~~possible data track density. FI~~n ~~FIG. 1c~~ five servo tracks 37 depicted as servo

14 tracks ~~(e.g.,~~ Sa, Sb, Sc, Sd and Se~~)~~ are shown in relation to three data tracks 30

15 depicted as data tracks Tk1, Tk2 and Tk3.

16

17   The servo tracks 37 are written on the disk surface 23 during

18 manufacturing at a servo track density that is about 150% of the maximum data

19 track density. ~~-T~~he ~~s~~Servo track density is determined by ~~determining~~ the

20 max~~imum,~~ read width and the min~~imum,~~ write width of a population of

21 the~~magnetic~~ heads 16. After writing the servo tracks 37~~wedges 25~~ at the servo

22 track pitch, the ~~actual~~ data track~~s~~ 30 can be written at any ~~disk~~ radial position

23 between the servo tracks 37. The data track density (TPI) can be selected from

24 predetermined levels or can be based on the location of a data sector 35.

25 Additional tests~~,~~ can be performed to determine the optimum data track density

26 of the ~~disk~~media surface 23. Each servo track 37 comprises radially similarly

27 situated ~~servo information in~~ servo sector~~wedges~~ 25 in the servo spokes. For

28 example, ~~(e.g.,~~ the ~~set of~~ servo track~~information~~ Se contains servo sectors 25 at

29 essentially the same radial distance from the ~~disk~~ center of the disk 12, the servo

30 track Sd contains servo sectors 25 at essentially the same radial distance from

31 the center of the disk 12, ~~form a servo track circumferrentially, set of servo~~

1   ~~information Se at essentially same radial distance from the disk center form~~

2   ~~another servo track circumferrentially, etc.)~~

3

4   FIGs. 1D to 1I show vertical zone formats in which different heads 16 on

5   different disk surfaces 23 may read/write at different linear frequencies (variable

6   BPI) on the data tracks 30 within a virtual cylinder 39.

7

8   FIG. 1D shows ~~an example diagram representing the general~~ zone 60

9   format~~layout~~ of the ~~a~~ disk drive 100, ~~with~~ N disks 12, ~~and~~ 2N heads 16, and

10 ~~depicting~~ different heads 16 in ~~a section~~ ~~z~~Zone 1 on different disks 12. FIG. 1E

11 shows another ~~example of capacity~~ zone 60 format~~layout~~ on the disk surface 23a

12 ~~surface a disk~~. FIG. 1F shows each ~~example of a series of radial~~ zones 60 on

13 the disk surface 23 ~~, Zone1 through ZoneM, on a disk surface, wherein each~~

14 ~~zone~~ includes multiple virtual cylinders 39. Zone 1 includes virtual cylinders 1 to

15 j, and zone M includes virtual cylinders 1 to i. The radial boundaries of the zones

16 60 are shown as dark circles, and the radial boundaries of the virtual cylinders 39

17 are shown as light circles. FIG. 1G shows ~~an example~~ representative data track

18 30 format~~layout~~ for the ~~each of several~~ virtual cylinders 39 in a zone 60~~(e.g.,~~

19 ~~Zone1),~~ on different disk surfaces 23 with corresponding heads 16. FIG. 1H

20 shows a data track 30 and ~~nother example~~ servo track 37 format~~and data track~~

21 ~~35 layout~~ for a zone 60 on different disk surfaces 23 with corresponding heads

22 16 in which ~~, wherein~~ the number of data tracks 30 and servo tracks 37 ~~and data~~

23 ~~tracks~~ in different virtual cylinders 39 of a zone 60~~(e.g., Zone1)~~ on different disk

24 surfaces 23 is~~are~~ the same. ~~And,~~ FIG. 1I shows a data track 30 and servo track

25 37 format for zones 60 on the disk surface 23 with a corresponding head 16 in

26 which ~~another example layout wherein the servo and~~ the data track 30 and servo

27 track 37 format~~layout~~ varies from ~~zone~~ zone 1 to zone M~~60 on a disk surface 23~~.

28 ~~In all of the above examples of vertical zoning layout according to the present~~

29 ~~invention, within a virtual cylinder 39, different heads on different surfaces may~~

30 ~~read/write at different linear frequencies on the data tracks (e.g., variable BPI).~~

31

1. ~~Overview of~~ Format Optimization

2. The ~~In one embodiment, a~~ vertical zoning ~~method according to the present~~

3. ~~invention~~ includes designing, /optimizing and ~~(selecting)~~ ~~for~~ two or more

4. recording frequency profiles ~~(i.e., per zone)~~ for a sample number of disk drives

5. ~~(e.g., performed~~ off-line during the disk drive development/design phase~~)~~. Then,

6. for a population of disk drives, in each disk drive, each head is assigned to one of

7. the predetermined frequencies for a given zone ~~(e.g.,~~ during the disk drive

8. manufacturing phase~~)~~. A ~~The assignment step includes assigning a~~

9. predetermined read/write frequency (BPI) is assigned to each head based on a

10. known number of head allocations and the head's performance ~~capability~~. A

11. head assigned to a higher frequency~~/density (HD)~~ records more bits on a track,

12. and a head assigned to a lower frequency~~/density (LD)~~ records less bits on a

13. track.

14.

15. Performance testing of the head and disk surface pairs occurs after full

16. read/write and servo calibration and optimization of the disk drive. I~~Referring to~~

17. ~~the example in FIG. 1A,~~ if the tested performance of hHead_1 at zZone_1 on disk

18. sSurface_1 of _dDisk_1 at a given frequency ~~(after full drive read/write and servo~~

19. ~~calibration/optimization)~~ is better than a ~~desired~~ target performance metric, then

20. ~~that (strong) head,~~ hHead_1~~,~~ is considered strong since it is capable of ~~to have~~

21. ~~some margin for~~ storing more information than ~~it was~~ originally accounted for.

22. Thus, the ~~designed~~ recording frequency can be increased at zZone_1 on disk

23. sSurface_1 of dDisk_1 for hHead_1 yet ~~so as to ensure the~~ its performance does

24. not fall below the ~~desired~~ target performance metric. If the tested performance of

25. hHead_2 at zZone_1 on disk sSurface_2 of dDisk_1 at the~~at~~ same frequency ~~(after~~

26. ~~full drive read/write and servo calibration/optimization),~~ is worse than a ~~desired~~

27. target performance metric, then ~~that (weak) head,~~ Hhead_2 is considered weak~~,~~

28. but can be compensated for by relaxing the frequency at which hHead_2

29. operates~~, so as~~ to ensure the target performance metric is met. Performing the

30. above trade_off between the heads for all the zones~~, without loss of overall~~

31. ~~capacity,~~ provides ~~resulting~~ frequency profiles ~~(i.e.~~ across the stroke~~)~~ that are

1   ~~comprising~~ vertically zoned frequency format profiles without loss of ~~overall~~

2   storage capacity.

3

4   Advantageously, ~~As the above example shows,~~ by compensating for

5   ~~h~~weak ~~Head~~_2, rather than failing the disk drive due to ~~the weak H~~head_2, the

6   vertical zoning improves ~~the disk drive~~ yield. ~~Without application of vertical~~

7   ~~zoning such a disk drive would not have passed the test limits, and hence would~~

8   ~~have failed.~~ Furthermore, the format optimizer uses the head ~~estimates of~~

9   performance (~~i.e.,~~ read/write frequency capability) ~~cumulative~~ distributions

10   ~~function~~ at every zone and a target performance metric~~,~~ to design a group of

11   read/write frequency format profiles for strong and weak ~~and strong~~ heads within

12   a given disk drive. The format optimizer also determines the optimal number of~~,~~

13   ~~for example,~~ strong versus weak ~~versus strong~~ heads.

14

15   The format optimizer does not determine which specific head is ~~actually~~ at

16   the high or lower ~~or higher~~ frequency, but does ~~only~~ provides a breakdown of the

17   number of heads at the high~~lower~~ frequency and the number of heads at the

18   low~~higher~~ frequency. The~~at~~ breakdown is fixed, performed off-line, and ~~is~~ used

19   during the head assignment~~ process~~. Then, in the head assignment~~ process~~

20   (~~e.g.,~~ during a manufacturing test~~ process~~), out of 2xN heads in a disk drive with

21   N disks, the number of heads ~~that have to be~~ assigned to each predetermined

22   frequency/~~format~~ is ~~also predetermined (e.g., number heads to assign to low~~

23   ~~frequency and number of heads to assign to high frequency)~~.

24

25   T~~As such,~~ the heads within a set of disk drives are allocated to the

26   predetermined group of read/write frequencies as part of the optimization

27   process to meet the storage capacity and yield requirements for the disk drives.

28   The allocation process allocates a number of the heads in a disk drive to ~~one of~~

29   the predetermined/~~designed~~ frequencies, however the specific assignment of a

30   particular head to a particular frequency is performed later during ~~as part of~~ the

31   assignment process ~~thereafter~~. For ~~In one~~ example, in a two~~2~~ read/write

1 frequency design (high frequency ~~density~~ and low frequency~~density~~) for a set of

2 disk drives ~~each~~ with ~~eight~~8 heads, in each disk drive for ~~z~~Zone 1 on all the disk

3 surfaces, any ~~five~~3 ~~heads~~ of the ~~eight~~8 heads are allocated to the high~~lower~~

4 frequency and any ~~three~~5 ~~heads~~ of the ~~eight~~8 heads are allocated to the

5 low~~higher~~ frequency ~~in the allocation process~~ based on the performance

6 measurements of ~~all~~ the heads in the set of the disk drives. Thereafter, the

7 specific assignment of each particular head to a particular predetermined

8 frequency is performed ~~as part of the assignment process~~. For example, in a

9 first disk drive ~~heads 1, 3, 4 are assigned to the low frequency, and~~ heads 2, 5, 6,

10 7, 8 are assigned to the high frequency and heads 1, 3, 4 are assigned to the low

11 frequency, whereas in a second disk drive ~~heads 2, 3, 8 are assigned to the low~~

12 ~~frequency, and~~ heads 1, 4, 5, 6, 7 are assigned to the high frequency and heads

13 2, 3, 8 are assigned to the low frequency. T~~, and so on, wherein~~ the specific

14 head assignments depend on the specific capability of the heads in each disk

15 drive.

16

17 The optimal number of heads per frequency ~~(i.e., head allocation)~~ is

18 determined at the same time that the group of read/write frequencies are

19 ~~designed/~~selected by the format optimizer~~,~~ by solving a joint constrained

20 optimization problem. For example, in a ~~the 8-head~~ disk drive with ~~eight~~8 heads

21 and~~withabove, for the case of two frequencies~~ a ~~(~~high frequency ~~(freq1)~~ and a

22 low frequency~~(freq2))~~ that are each a different ratio of a reference frequency~~at a~~

23 ~~ratio to a frequency~~ freq, in each vertical zone, allocating ~~two~~2 heads to the high

24 frequency~~1~~ and six~~allocating~~ 6 heads to the low frequency~~2,~~ provides a specific

25 ~~first~~ storage disk drive capacity. Changing the~~said~~ frequency ratio ~~of the~~

26 ~~frequencies~~ and the number of heads allocated to each frequency~~,~~ provides a

27 different storage capacity ~~for that disk drive~~. Thus, ~~As such,~~ the disk drive

28 storage capacity is a function of the number of heads multiplied by the frequency

29 allocated to each head per zone. —For example, if a nominal disk surface data

30 storage ~~level capacity~~ is 1 unit, and if the high frequency ~~1~~= 4/3 x the reference

31 frequency and the low frequency~~2~~ = 2/3 x the reference frequency, then one

1 head can be at ~~the high~~ frequency~~1~~ for every one head at ~~the low~~ frequency~~2~~, to

2 maintain ~~whereby~~ the average ~~disk~~ surface ~~data storage~~ ~~capacity~~ ~~at~~is 1 unit.

3

4   The head performance distributions represent percentages of the heads in

5 the disk drives than can operate at different frequencies. For example, the head

6 performance distribution ~~i~~as a BPI distribution that represents the head frequency

7 capability at a target performance metric. ~~–~~Using the head performance

8 distributions (~~i.e.,~~ ~~the~~ head read/write frequency capability distributions at the

9 target performance metric for every zone), the number of heads, the format of the

10 virtual cylinder~~s~~, and ~~the~~a desired ~~storage~~ capacity, the format optimizer

11 determines the frequency for each virtual cylinder ~~in each~~ zone ~~in each virtual~~

12 ~~cylinder~~ and the number of heads in each disk drive allocated to each frequency~~,~~

13 ~~in order~~ to achieve th~~e~~at desired ~~storage~~ capacity. Thereafter, in the assignment

14 process (~~e.g.,~~ as part of ~~a~~ testing ~~of~~ each disk drive~~)~~, each ~~specific~~ head in a

15 population of disk drives is assigned to one of the predetermined frequencies

16 based on the allocation criteria and ~~the~~ specific head performance. For ~~an~~

17 example~~,~~ ~~in a~~ ~~4 head~~ disk drive ~~with four~~4 heads, the format optimizer considers

18 ~~three~~3 heads at ~~the high~~ frequency~~1~~ and ~~one~~1 head at ~~the low~~ frequency~~2~~, then

19 ~~two~~2 heads at ~~the high~~ frequency~~1~~ and ~~two~~2 heads at ~~the low~~ frequency~~2~~, and

20 then ~~one~~1 head at ~~the high~~ frequency~~1~~ and ~~three~~3 heads at ~~the low~~ frequency~~2~~.

21 Thus, ~~And in each case,~~ the format optimizer us~~es~~ing the ~~estimated~~ head

22 performance ~~cumulative~~ distribution ~~functions~~ to determine~~s~~ the ~~disk drive yield.~~

23 ~~The head performance distributions (e.g., BPI distributions) represent~~

24 ~~percentages of the heads in the disk drives than can operate at different~~

25 ~~frequency densities. This allows the format optimizer to determine the~~ storage

26 capacity and yield ~~and capacity.In the description of the example embodiment~~

27 ~~herein, head performance distribution, such as a BPI distribution, represents~~

28 ~~head frequency capability (probability) cumulative distribution at a target~~

29 ~~performance metric.~~

30

1   In one version of the optimization process, the ~~disk drive~~ yield is

2   maximized while meeting a constraint on storage capacity. In another version,

3   the storage capacity is maximized while meeting a constraint on ~~disk drive~~ yield.

4   In the former case, the format optimizer uses a format where the maximum

5   number of disk drives qualify and the fewest number of disk drives fail to reach

6   the required storage capacity~~higher frequency is freq1 and the lower frequency is~~

7   ~~freq2.~~ For ~~In the~~ example, in a ~~4 head~~ disk drive with four~~4~~ heads and a nominal

8   disk surface data storage~~capacity~~ of 1 unit, allocating two~~2~~ heads to the high

9   frequency~~1~~ and two~~2~~ heads to the low frequency~~2,~~ provides a nominal data

10   ~~surface capacity of 1 unit, and~~ storage capacity ~~of~~ 4 units ~~for the disk drive.~~ In

11   the later case, the format optimizer uses a format where the maximum number of

12   disk drives reach the required storage capacity and the fewest number of disk

13   drives fail to qualify. For example, in a disk drive with four~~4~~ heads and a nominal

14   disk surface data storage~~capacity~~ of 1 unit, allocating three~~If 3~~ heads ~~are~~

15   ~~allocated~~ to the high ~~higher~~ frequency~~1~~ and one~~1~~ head to the low ~~the lower~~

16   ~~frequency~~ frequency~~2~~ provides~~,~~ a higher data storage ~~capacity~~ of ~~(i.e. 4.66 and~~

17   ~~2/3)~~ units~~is achieved for the disk drive. In that case, the format optimizer lowers~~

18   ~~the zone recording frequencies to meet that constraint of capacity of 1 unit per~~

19   ~~surface. As such, for 2 heads at freq1 and 2 heads at freq2, the format optimizer~~

20   ~~manipulates the difference of those frequencies such that surface capacity~~

21   ~~always reaches 1 unit, but maximizes yield whereby a maximum number of disk~~

22   ~~drives qualify and fewest number of disk drives fail to reach required capacity.~~

23

24

25   Thus, ~~As such, according to one embodiment of the present invention, a~~

26   the vertical zoning ~~approach~~ for variable BPI ~~design~~ includes ~~use of~~ an off-line

27   predetermined per zone format design ~~of formats~~ based on disk drive data

28   collection and head performance ~~(joint) BPI~~ distribution extraction ~~methods.~~ In

29   one version, a fixed predetermined zone boundary format~~layout~~ is used to design

30   multiple frequency BPI formats based on representative or actual joint BPI

31   distributions at one or more desired target performance metrics (such as off-track

1   symbol error rate) and, wherein the joint BPI distributions are extracted from a

2   finite pre-selected set of disk drives.

3

4   The collected data is used to extract thesaid joint BPI distributions for the

5   heads at every (pre-selected) zone, and the per zone design of low/high and low

6   data density formats for the heads is performed off-line. The format optimizer

7   solves a constrained joint optimization process off-line to obtain thesaid format

8   designs, using well-known constrained optimization routines. Using joint BPI

9   distributions allows consideration of potential correlation of BPI capability of the

10 heads across the stroke as well as the individual contribution of each head to the

11 storage overall drive capacity (or areal density) and yield.

12

13 The off-line format design of formats allows the format optimizer to

14 consideration of other potential constraints that may arise, as additional

15 constraints within the optimizer, and hence solved by the optimizer. For

16 example, as more information is obtained in quantifying the thermal stability

17 constraints of the disks recording media (which in turn places an upper bound

18 onef linear bit density for the heads) the off-line format design does provides the

19 ability of not exceeding theese constrainlimits. Likewise, iIf there are data rate

20 constraintlimitations in either the write process capability or the ASICs

21 component capability, such constraints may be cast within the joint constrained

22 format optimizer to ensure thesaid constrainlimits are not exceeded.

23

24 Data Overview of Measurement Process

25 AIn one implementation of the method of the present invention, a

26 measurement procedure is used to collect data, from which such that after

27 processing of the collected data, one-dimensional (1-D), two-dimensional (2-D)

28 and as well as three-dimensional (3-D) joint BPI (probability) distributions at a

29 desired read/write target error rate (or any other choice of metric) can be

30 extracted. -Data is collected based on head capability measurements taken at

31 different radial positions onef the disk. The collected data is used to extract 1-D,

1 ~~2-D and 3-D empirical distributions at a target choice of performance metric.~~ The

2 ~~dimensions are dimensions of the distributions, and the~~ distributions represent

3 the capability of each head at different radial positions. For example, several

4 disk drives which collectively include 1000 heads are selected for measurement,

5 and ~~. In a measurement process,~~ record/playback error rate measurements of

6 the 1000 heads from z~~Z~~one 1 to z~~Z~~one 24 of the disk surfaces at different

7 frequencies are obtained. Thereafter, in post-measurement data processing~~:~~ (a)

8 the BPI capability of each~~very~~ head at a fixed target performance metric at ~~e.g.~~

9 z~~Z~~one 1 is determined ~~in order~~ to obtain a 1-D BPI distribution, (b) the BPI

10 capability of each~~the~~ head at a fixed target performance metric at ~~e.g.~~ z~~Z~~ones 1

11 and z~~Z~~one 5 is determined ~~in order~~ to obtain a 2-D BPI ~~joint~~ distribution, and (c)

12 the BPI capability of each~~the~~ head at a fixed target performance metric at ~~e.g.~~

13 z~~Z~~ones 1, z~~Z~~one 5 and z~~Z~~one 20 is determined ~~in order~~ to obtain a 3-D BPI ~~joint~~

14 distribution.

15

16 The BPI distributions are then passed~~used as input~~ to the format optimizer

17 to solve three constrained optimization problems to provide head frequency per

18 zone allocations. The three constrained optimization problems~~, wherein:~~ (1) ~~one~~

19 ~~problem~~ maximizes the ~~disk drive~~ yield while preserving the ~~same~~ storage~~drive~~

20 capacity, (2) ~~another~~ maximizes the storage~~disk drive~~ capacity while preserving

21 the ~~same drive~~ yield ~~and~~, and (3) ~~another~~ maximizes the ~~disk drive~~ yield while

22 ensuring a ~~desired~~ target storage ~~drive~~ capacity is met at a fixed target ~~track-per-~~

23 ~~inch (TPI)~~. C~~Additionally,~~ customer related or ~~application-specific integrated~~

24 ~~circuit (ASIC)~~ data rate ~~(limitation)~~ constraints are also consider~~utilized~~. ~~-~~The

25 format optimizer can ~~is capable of~~ solv~~eing~~ any ~~one~~ of the~~se~~ ~~above-mentioned~~

26 three problems, and ~~wherein~~ one problem can take priority over another

27 depending on the process phase. For example, at an earli~~y~~er development

28 phase ~~of a program~~ where the disk drive components are not matured ~~yet~~,

29 meeting the storage ~~drive~~ capacity may be a challenge. In that phase~~case~~, the

30 format optimizer can ~~be used to~~ design the variable BPI format profiles by solving

31 the second problem ~~above~~. Then, a~~As~~ the disk drive components mature, ~~and~~

1 ~~such that~~ meeting the storage~~drive~~ capacity becomes easier and meeting the

2 ~~drive~~ yield becomes more important, the first problem may be solved ~~considered~~

3 ~~instead.~~ Thereafter, as part of a test process, an assignment algorithm ~~is used to~~

4 ensures the appropriate head assignments to the predetermined high and /low

5 data density ~~(pre-specified)~~ formats per head and per zone or across the ~~head~~

6 strokes~~,~~ based on the head allocation breakdown of the format optimizer.

7

8 The y~~Disk drive y~~ield is improved while meeting the ~~desired~~ target storage

9 ~~drive~~ capacity by allowing a frequency format ~~layout~~ with ~~(e.g.,~~ high and low

10 frequencies and y~~) with~~ a predetermined number of high and low performing

11 head allocations. U~~s~~tilizing realistic constraints such as ASIC data rate

12 limitations, the same fixed target TPI is maintained by increasing the average

13 target BPI across the ~~head~~ stroke ~~on a disk surface~~ to achieve the target~~desired~~

14 ~~disk drive data~~ storage capacity. As such, head performance variation from one

15 head to the next head in the disk drive ~~(and~~ for ~~across~~ the head ~~stroke~~ across the

16 stroke of the~~a~~ disk surface~~)~~ is u~~s~~tilized to ~~allow~~ increas~~e~~ing the storage capacity

17 ~~areal density of the stored information~~ while preserving the ~~same overall disk~~

18 ~~drive~~ yield. For ~~In one~~ example, the~~a~~ vertical zoning format~~layout~~ use~~method~~

19 ~~according to the present invention utiliz~~es several design constraints to improve

20 ~~the drive~~ yield using a variable high and low/~~high~~ BPI design with a fixed

21 predetermined number of head allocations as a function of the zones while

22 meeting the target storage capacity at a fixed target TPI. The h~~H~~ead

23 performance variation or correlation across the stroke is also u~~s~~tilized.

24

25 Further, ~~the method of present invention takes into consideration~~ the

26 difference in data storage~~storage capacity~~ of two or mores zones on a disk

27 surface is considered~~,~~ as it affects storage ~~overall disk drive~~ capacity. The

28 storage ~~disk drive~~ capacity is defined as a weighted combination of the zone

29 capacities across the stroke on each disk surface in the disk drive. A correlation

30 in the head performance statistics is extracted from one head to another head,

1   and for every ~~given~~ head considered in a set of disks drives across the ~~head~~

2   stroke on each disk surface.

3

4   The joint constrained optimization ~~process~~ determines a per zone target

5   high and low ~~low/high~~ data density format~~/layout~~. The optimization ~~process~~ takes

6   into account constraints including customer related requirements such as ~~the~~

7   ~~requirement of a~~ minimum logical block count ~~(LBA)~~, monotonic data rate, and

8   maximum data rate ~~requirements~~ at the outer zone ~~areas~~ which can be

9   formulated into ~~(additional)~~ constraints. ~~Head allocation and assignment~~

10 ~~according to the present invention improves manufacturing yield and provides a~~

11 ~~disk drive with minimal performance degradation (i.e., sequential or random~~

12 ~~throughput as well as test process time).~~

13

14 <u>Example Implementation</u>

15 FIG. 2A shows ~~an example~~ function and flow diagram ~~of an example~~

16 ~~implementation of the above-described method according to the present~~

17 ~~invention~~ for generating <u>the</u> optimal data density format~~/layout~~ shown ~~by example~~

18 in FIG. 1A. ~~The~~ <u>function and flow diagram</u>~~example method in FIG. 2A~~ includes~~:~~

19 a data ~~collection/measurer~~<u>ment</u> ~~process (block)~~ 62, a <u>post-measurement</u> data

20 ~~post-measurement~~ process<u>or</u> ~~(block)~~ 64, <u>a</u> format optimizer ~~process (block)~~ 66

21 <u>and a</u>~~,~~ format generator ~~process and head assignment process (block)~~ 68~~,~~

22 ~~example embodiments of which are described below.~~

23

24 <u>Data ~~Collection/~~Measurer</u>~~ment process~~

25 <u>The data measurer 62 takes data measurements for every zone at a finite</u>

26 <u>number of frequency samples.</u>

27

28 <u>T</u>~~In one embodiment,~~ the <u>data</u> measurer~~ment block~~ 62 implements a

29 measurement procedure <u>that</u> includ<u>es</u>~~ing~~ the steps of:

30 <u>(1)</u>~~.~~ __ Creat<u>e</u>~~ing~~ several different predetermined linear <u>bit</u> density format

31 profiles <u>includ</u>~~comprising~~ a profile of different frequencies per zone across the

1   actuator stroke, such as e.g. a first profile including high frequency freq1 1 for

2   zZone_1, high frequency freq1 2 for zto Zone 2, ..., high frequency 1M for

3   zZone_M,; and a second profile including low frequency2 1 for zZone_1, low

4   frequency2 2 for zZone 2, ..., low frequency2 M for zZone_M, etc., to be loaded

5   on a representative number of disk drives selected for the measurement process

6   (or if possible on all of the available disk built drives for that build);

7   (2). __-Loading a frequency format profile;

8   (3). __Performing read/write and servo optimization and calibration;

9   (4). __Takeing head performance measurements including e.g. (off-track)

10 mean square error (MSE) or quality metric (QM) and/or symbol error rate (SER)

11 measurements at pre-selected frequencies for preferably all available zones, and

12 saveing the data; and

13   (5). __-Repeating steps 2-4 above for all the remaining frequency format

14 profiles.

15

16   The above steps are performed for the selected disk drives in the

17 measurement process.

18

19   Thus, in the disk drive 100,As such density is selected and the data is

20 recorded on a data sector 35portion of the diskmedia surface 23 at the selected

21 data density by positioning thea magnetic head 16 abutting the data sector

22 portion 35 of the diskmedia surface 23, and sending the appropriate write signals

23 to the write element (not shown) of the magnetic head 16. Typically, a sample of

24 data is recorded on the disk surface 23 such that a significant number of errors

25 are detected (such as e.g., ten 10 errors per error rate measurement), is

26 recorded on the diskmedia surface 23 to obtain a statistically representative

27 sampling of the error rate for the data sector portion 35 of the diskmedia surface

28 23. _Thereafter, the recorded data is read by the read element (not shown) of the

29 magnetic head 16, and the data read is stored by the host computer system 54

30 for evaluation. An error rate of the recorded data is measured or compiled by

31 comparing the actual written data with the read data, element-by-element. The

1   ~~Suitable methods of determining the~~ error rate can be determined using a ~~include~~

2   ~~actual~~ bit error measurement in which a bit of data read from the disk~~media~~

3   surface 23 is compared with the correct bit, ~~a~~or bit steam measurement in which

4   a bit stream of data read from the disk surface 23 ~~a correct bit stream in~~ is

5   compared with a correct bit stream, or a ~~measured bit stream. An alternative~~

6   ~~method uses the~~ mean square error metric measurement ~~method~~ in which a

7   waveform read from the disk~~media~~ surface 23 is compared with an ideal

8   waveform to provide an error signal that is squared and summed to form the

9   error metric.

10

11   In this description, a component distribution is defined as~~to be~~ a ~~(random)~~

12   variation (~~i.e.,~~tolerance) of a pre-specified ~~(target)~~ nominal component

13   parameter such as a head write/read width, and a ~~the term~~ distribution is defined

14   as a~~the~~ probability distribution function ~~(PDF)~~. During the early product

15   development ~~process~~, when the head performance distributions are wide and

16   unreliable, data from a matur~~ed~~ set of disk drives is used for extracting reference

17   ~~(joint)~~ BPI distributions at a target performance metric such as on-track symbol

18   error rate, off-track symbol error rate, on-track mean square error ~~(e.g., off/on~~

19   ~~track error rate~~or off-track mean square error~~)~~. Later~~in the process~~, when the

20   ~~amount of~~head performance variations from one phase to the next in the

21   distribution is expected to be minimal, new sets of measurement data are

22   collected using a selected ~~plurality/~~population of disk drives at their more

23   matur~~ed~~ stages.

24

25   Thus, a number of BPI formats including the nominal target format are

26   selected. _Then, on-track or off-~~or on-~~track symbol error rate or mean square

27   error ~~MSE~~measurements are taken at different pre-selected locations of the disk

28   surfaces, such as the ~~e.g.,~~outer, middle and inner zone~~s~~. The performance

29   measurements can be limited to ~~are taken (in one example scenario described~~

30   ~~further below, the choice is limited to~~these~~said~~ three zones~~,~~ to reduce the

31   measurement time~~for performing measurement)~~. However, preferably the

1 <u>performance</u> measurements over multiple zones ~~can be performed~~ and other

2 measurements such as off-track ~~measurements (e.g., 747 measurements)~~ can

3 be performed~~also be taken~~. The nominal formats are generated from the data.

4

5 Two or more different linear <u>bit</u> density format profiles can be loaded at a

6 time. In one example, two variable BPI format per zone design (~~low/~~high <u>and low</u>

7 <u>data</u> density format profiles) can be created for ~~the purpose of~~ measurement data

8 collection during every build. In this way, more statistical data can be collected

9 from more disk drives, however~~,~~ there will be only two frequency samples per

10 zone available for ~~data~~ post-measurement <u>data</u> processing.

11

12 <u>P</u>~~Raw Data~~ post-M~~m~~easurement Data P~~-p~~rocessor

13 ~~P~~<u>I</u>~~n the above steps, measurements (e.g. either MSE or SER) for every~~

14 ~~zone are taken at a finite number of frequency samples. In~~ post-measurement

15 <u>data processor</u> ~~processing (post-processing) block~~ 64~~,~~ us<u>e</u>~~ing~~ the available

16 performance metric~~,~~ measurements ~~are used~~ to calculate each head's frequency

17 performance<u>, for instance as</u> ~~(e.g.,~~ kilo flux per inch (kFCI) or kilo bits per inch

18 (kBPI)<u>,</u>~~)~~ at a ~~given~~ target performance metric. The performance of every head at

19 every zone is determined as a function of <u>the</u>~~said~~ read/write frequency profiles

20 used for the measurements.

21

22 For example, if <u>six</u>~~6~~ different frequency profiles are used, then for every

23 head per zone, the <u>data</u> measure~~rment process~~ 62 provides measured data as a

24 function of <u>six</u>~~6~~ frequency samples at a target <u>performance</u> metric. In the post-

25 measurement <u>data</u> process<u>or</u> 64, ~~all~~ the measured data is sorted and <u>the</u>

26 performance of every head at every zone at the <u>six</u>~~6 different~~ frequency samples

27 is extracted to generate frequency capability histograms at a target performance

28 metric~~ (e.g. error rate)~~.

29

30 ~~Referring to~~ FIG. 2B <u>shows a graph of playback error measurement for a</u>

31 <u>head at a zone at different recording frequencies. The curve shows head</u>

1 performance as a function of frequency (BPI). T, ~~the samples can be depicted in~~

2 ~~a two-dimensional graph wherein the~~ x-axis ~~(horizontal)~~ is the read/write

3 frequency in ~~(e.g., frequencies 1 through 6,~~ kBPI at the outer diameter ~~OD)~~, and

4 the y-axis ~~(vertical)~~ is the on-track symbol error rate ~~o~~ ~~measurement~~ in a log scale

5 ~~for Head1 at zone 1 for each of the~~ said 6 frequencies. ~~E(log SER) (in FIG. 2B,~~

6 each ~~frequency~~ ~~sample data~~ sample 70 is depicted as ~~a~~ "+", each curve fit point

7 72 is depicted as "o" and each projected frequency 74 is depicted as "◊" ~~)~~.

8

9   In the illustration, head 1 at zone 1 in disk drive 3 is measured at six

10 frequency samples. The curve is generated using a least square polynomial fit to

11 the six frequency samples. The projected frequency (BPI) for a target on-track

12 symbol error rate is extracted from the curve by interpolation or extrapolation.

13 For example, if the target on-track symbol error rate is 10^{-8} then the projected

14 frequency is determined by interpolation, whereas if the target on-track symbol

15 error rate is 10^{-6} then the projected frequency is determined by extrapolation.

16 The on-track symbol error rate varies ~~measurement can vary e.g. from 1e^{-4} (i.e.,~~

17 ~~1x10^{-4}) to 1e^{-7} (i.e., 1x10^{-7})~~ as a function of ~~the~~ 6 frequenc~~y~~~~ies,~~ and ~~wherein the~~

18 ~~error rate~~ increases as the ~~read/write~~ frequency ~~(density)~~ increases.

19

20   The nominal kBPI (before vertical zoning) and the kBPI gain relative to the

21 nominal kBPI are also shown. Head 1

22

23 can be classified as a strong head because there is reasonably significant margin

24 before its on-track symbol error rate of −9.1 (log) at a nominal frequency/kBPI of

25 ~ 188 can be changed to a projected on-track symbol error rate of −6.22 at a

26 frequency/kBPI of ~ 217. Hence, there is a total kBPI gain of ~ 29, allowing the

27 nominal frequency to increase by 15% while meeting the target on-track symbol

28 error rate performance metric of 6×10^{-7}. Thus, head 1 of disk drive 3 has a

29 frequency capability of about 217 at the target on-track symbol error rate of 6×10^{-7}

30 ^{7}, which provides a sample for the generation of a histogram.

31

1 FIG. 2C shows a histogram of the frequency capabilities of the heads in a

2 set of disk drives at a zone at a target performance metric. The histogram 76 is

3 constructed using the projected frequencies determined in FIG. 2B for the heads

4 in the selected disk drives reading from zone 1 at the target on-track symbol error

5 rate of 6×10^{-7}. The x-axis is the projected frequency capability at the outer

6 diameter, and the y-axis is the number of heads. The histogram is extracted and

7 empirical, has a normal distribution fit and has a width that corresponds to the

8 head performance variation.

9

10 Additional histograms ~~—— To determine frequency capability of e.g.~~

11 ~~Head1 at Zone1 at a target error rate of $1e^{-6}$ (i.e., 1×10^{-6}), a curve is fit (e.g.,~~

12 ~~using known curve-fitting techniques such as least squares polynomial fit) to the~~

13 ~~6 samples, to determine by interpolation the frequency value that gives rise to~~

14 ~~that target error rate (in FIG. 2B, each curve fit point 72 is depicted by a "o"). If~~

15 ~~the target error rate is at $1e^{-8}$ (i.e., 1×10^{-8}) then the frequency value that gives rise~~

16 ~~to that target error rate is determined by extrapolation (in FIG. 2b, the projected~~

17 ~~or extrapolated frequency value 74 is shown as a diamond shape). The process~~

18 ~~for that target error rate is performed for Zone1 for all the heads in the selected~~

19 ~~disk drives used in the measurement process 62, to create a histogram (FIG. 2D)~~

20 ~~of the frequency capabilities of all the heads in the disk drives at Zone1 at that~~

21 ~~fixed target error rate.~~ are constructed ~~The process is the same~~ for ~~all~~ the

22 remaining zones based on the frequency capabilities determined from the graphs

23 based on the performance measurements taken at the remaining zones so that ~~.~~

24 ~~As such, using~~ every available head considered in the disk drives under

25 measurement has~~,~~ BPI histograms ~~can be extracted~~ at a ~~given~~ target

26 performance metric per zone.

27

28 ~~—— FIG. 2B shows an example curve of error rate of performance (SER) as a~~

29 ~~function of BPI (e.g., SER at 6 different BPI/frequency samples) for a head~~

30 ~~located at the outer diameter (OD) of the disk. Also shown is extracted~~

31 ~~BPI/frequency capability value of that head at a zone (e.g., OD) for the specified~~

1 ~~target error rate, using interpolation/extrapolation (i.e., if the specified desired~~

2 ~~target error rate is outside the performance range, extrapolation or interpolation,~~

3 ~~such as polynomial fit, is used as necessary). The amount of BPI gain, or margin~~

4 ~~relative to the nominal BPI setting, is also specified and marked.~~

5

6 ———Thus, ~~The~~ performance measurements are provided for each head

7 at each zone in the selected disk drives, the graphs are generated for each head

8 at each zone, the frequency capabilities for each head at each zone are

9 determined for a target performance metric, and the histograms are constructed

10 for each head at each zone for the target performance metric. Likewise, ~~above~~

11 ~~process is performed for all the heads considered in the measurement~~

12 ~~procedure, and a BPI/frequency capability of all heads at a given target error rate~~

13 ~~for every zone is generated. Thus, in this manner, BPI/frequency capability~~

14 ~~histograms for every zone at a specified target error rate are constructed.~~ ~~I~~if a~~the~~

15 histogram of head BPI capability at a target performance metric ~~error rate~~ of a

16 ~~every~~ zone (such as an intermediate zone) is not available~~,~~ then the histogram

17 for that zone can be constructed by -interpolation or /extrapolation ~~is preformed~~

18 ~~to construct histograms for the intermediate zones.~~ The histograms can be used

19 to estimate a BPI distribution.

20

21

22 FIG. 2D shows a joint BPI distribution calculated from the histograms of

23 the heads in the measured disk drives at a——— ~~The constructed histograms are~~

24 ~~used to calculate cumulative performance distribution functions (CDF) of the~~

25 ~~head frequency (e.g., BPI) capability at a~~ ~~given~~ target performance metric. The

26 joint BPI distribution is a 2D distribution based on the histograms in FIG. 2C ~~error~~

27 ~~rate performance metric) as input to the format optimizer.~~ at the target on-track

28 symbol error rate of 6×10^{-7}. The x-axis is the BPI capability of the heads at the

29 middle diameter (MD) of the disks, the y-axis is the BPI capability of the heads at

30 the outer diameter (OD) of the disks, and the z-axis is the calculated number of

31 heads divided by the total number of heads. The joint BPI distribution provides

1   an estimate of the probability that the heads meet the target performance metric

2   at the MD and the OD.

3

4   The joint BPI distribution may predict, for example, that 10% of the heads

5   in the measured disk drives can operate at a high frequency of 1.5 x the

6   reference frequency, 50% of the heads can operate at a high frequency of 1.25 x

7   the reference frequency, 90% of the heads can operate at the reference

8   frequency, and 99.9% of the heads can operate at a low frequency of 0.75 x the

9   reference frequency.

10

11   Such performance distribution functions are designated as marginal,

12   individual or per zone distributions. In one example the distribution functions

13   include one-dimensional (1-D), two-dimensional (2-D) and three-dimensional (3-

14   D) joint BPI/frequency capability CDF, calculated at the same specified target

15   error rate. Marginal or one-dimensional distribution functions from the joint

16   distribution functions can also be calculated.

17

18   A version of estimating performance (e.g., frequency capability)

19   cumulative distribution functions at a given desired target performance metric

20   and zone is described. A number of frequency format profiles can be generated

21   and tested on a set of disk drives to ensure proper operation. The frequency

22   formats are generated and used to exploit every head's linear density or

23   frequency/BPI sensitivity at every zone. Thus, Ffor example, the linear bit density

24   sensitivity of every head at a zZone K (where K ranges from 1 to M zones) at the

25   six frequency samples is determined. To do so, the performance of every head

26   is measured (after full drive read/write and servo calibration/optimization) at each

27   frequency at ZoneK. If frequency 1Freq1 K, frequency Freq2 K . . ., . . .,

28   fFrequency 6 K are the frequency samples selected frequencies at zZone K, in

29   the measurement process, every head is positioned on a track (e.g., the same

30   track) in at zZone K and the record/playback performance of each head is

1   measured at every frequency ~~sample~~ using a ~~target~~ performance metric ~~of choice~~

2   ~~(e.g., off-track symbol error rate (SER))~~.

3

4   The BPI distributions can be calculated at the target performance metric

5   as 1D, 2D or 3D distributions that are marginal, individual or per zone

6   distributions, respectively. The format optimizer uses the estimated frequency

7   capability BPI distributions for every zone at the target performance metric to

8   determine the storage capacity and yield.

9   ~~For example, FIG. 2B shows the on-track SER performance of a selected~~

10 ~~head e.g. Head1, at Zone1, and the best least square polynomial fit curve. For a~~

11 ~~desired on-track target SER of 6e-7, the BPI capability of the (randomly) selected~~

12 ~~Head1 at that target performance metric can be projected by extrapolating the~~

13 ~~data (interpolation is performed if the desired on-track target SER is in the~~

14 ~~performance range, and extrapolation is performed otherwise). FIG. 2B shows~~

15 ~~the projected BPI capability of that head at an on-track SER of $6e^{-7}$ (i.e., $6x10^{-7}$).~~

16 ~~The original nominal kBPI (i.e., before the application of vertical zoning) is also~~

17 ~~shown. The head can be classified as a strong head because there is a~~

18 ~~reasonably significant amount of margin before the on-track SER performance of~~

19 ~~this head can be changed from its nominal frequency/kBPI of ~ 188 with an on-~~

20 ~~track (log of) SER of –9.1 to a projected on-track (log of) SER of –6.22 operating~~

21 ~~at a frequency/kBPI of ~ 217. Hence, there is a total kBPI gain of ~ 29, allowing~~

22 ~~increase in the nominal frequency by 15 % while meeting the desired target on-~~

23 ~~track SER performance metric of 6e-7 (i.e., $6x10^{-7}$). Thus, for example, Head1 of~~

24 ~~disk drive3 has a frequency capability equal to 217 at an on-track SER of 6e-7~~

25 ~~(i.e., $6x10^{-7}$), which is noted for Head1 as one sample for generation and~~

26 ~~extraction of empirical histograms.~~

27

28 ~~Performing the above steps for all the heads of all the disk drives~~

29 ~~considered in the measurement process, allows extraction of the empirical~~

30 ~~histograms of frequency capability at on-track SER of $6e^{-7}$ (i.e., $6x10^{-7}$) for such~~

31 ~~heads, as shown by example in FIG. 2D. The y-axis shows the number of heads~~

1 ~~that meet the interpolated/extrapolated (i.e., projected) frequency capability that~~

2 ~~is shown on the x-axis. The extracted (empirical) histogram can be used to~~

3 ~~estimate the probability cumulative distribution function. The width of each~~

4 ~~histogram 76 corresponds to a variance of the head performance histogram,~~

5 ~~wherein an objective of the present invention is to improve the disk drive yield~~

6 ~~and capacity, and as a result reduce that variance.~~

7

8 ~~FIG. 2C shows an example joint BPI distribution plot. Such BPI~~

9 ~~distributions may predict that, for example, 10% of the heads in the disk drives~~

10 ~~for which measurement was performed, can operate at a frequency density of 1.5~~

11 ~~x freq (wherein freq is a reference frequency), and 50% can operate at density of~~

12 ~~1.25 x freq, and 90% can operate at density of 1.0 x freq, and 99.9% can operate~~

13 ~~at density of 0.75 x freq, etc. Using the estimated frequency capability~~

14 ~~cumulative distribution functions at the target performance metric and every~~

15 ~~zone, the format optimizer determines the disk drive yield and capacity.~~

16

17 ~~FIG. 2C is an example of a 2-D joint (i.e. outer diameter (OD) and middle~~

18 ~~diameter (MD)) BPI cumulative distribution function (CDF) at a target~~

19 ~~performance metric (e.g. on-track symbol error rate of 6e-7). The x-axis shows~~

20 ~~the BPI capability of all heads (i.e. from all the disk storage devices considered in~~

21 ~~the measurement phase) at MD AND y-axis is the BPI capability of all heads at~~

22 ~~OD. The z-axis shows the (calculated) number of heads divided by the total~~

23 ~~number/population of heads i.e., an estimate of probability that those heads have~~

24 ~~a joint BPI capability at OD AND MD of less than or equal to any given desired~~

25 ~~values. BPI capability for e.g. at OD in the above description it is meant that~~

26 ~~while operating at (or below, i.e., if considering CDF) a given BPI, after full~~

27 ~~Read/Write and servo calibration and optimization, meeting a desired given~~

28 ~~target performance metric of choice at OD. Thus, the aforementioned description~~

29 ~~of BPI capability can similarly be extended to joint BPI capability.~~

30

31 <u>Format Optimizer</u> ~~process~~

f35

1

2   The format optimizer ~~process block~~ 66 provide~~comprises~~ a ~~variable~~ BPI

3   optimization. The format optimizer 66 solves ~~process for solving multiple (e.g.,~~

4   ~~three)~~ constrained optimization problems in response to various inputs. ~~given the~~

5   ~~inputs: number of frequency formats (i.e., desired number of different read/write~~

6   ~~frequencies), number of heads in each disk drive, and the~~said BPI ~~distributions.~~

7   The first problem maximizes the ~~drive~~ yield while preserving the storage ~~same~~

8   ~~drive~~ capacity, the second problem maximizes the storage ~~drive~~ capacity while

9   preserving the ~~same drive~~ yield, and the third problem maximizes the ~~drive~~ yield

10   while reducing the track density and meeting the storage capacity~~allowing~~

11   ~~reduced/relaxed TPI such that the desired target drive capacity can be met.~~ The

12   inputs include the number of different read/write frequencies (frequency profiles

13   or formats), the number of heads in each disk drive, the BPI distributions, and the

14   nominal storage capacity. The BPI distributions indicate the frequency capability

15   distribution of the heads at a target performance metric.

16

17   ~~T~~

18

19   ~~   The format optimizer 66 inputs the~~said BPI ~~distributions, a desired disk~~

20   ~~drive capacity, the total number H of heads per disk drive and the number N of~~

21   ~~frequency profiles or vertical zones (i.e., frequency per zone across a~~ disk~~media~~

22   ~~surface stroke). Given the frequency capability distribution of heads at a target~~

23   ~~performance metric, the total number of vertical frequency formats (F), the total~~

24   ~~number of heads per drive (H) and the nominal drive capacity,~~ the format

25   optimizer 66 simultaneously searches through a~~all possible~~ continuous range of

26   all possible frequency capabilities to maximize the ~~drive~~ yield such that the

27   ~~desired~~ nominal storage ~~drive~~ capacity is met. The format optimizer 66 can also

28   perform~~solve~~ the same operation with the ~~problem, but the drive~~ storage capacity

29   and the ~~drive~~ yield interchanged~~interchanged~~.

30

1   The ~~As such, in one example, the~~ format optimizer 66 can ~~optimizes~~ high

2   and ~~/~~low data density as a function of the zone~~s, to improve the drive yield and~~

3   ~~meet a fixed target capacity. The format optimizer also optimizes capacity while~~

4   ~~achieving a fixed nominal drive yield, wherein the nominal yield is before the~~

5   ~~application of vertical zoning according to the present invention.~~ For~~In~~ the~~said~~

6   example, in a disk drive with eight~~of F=2 formats (high density and low density)~~

7   ~~and H=8~~ heads ~~16 in a disk drive 100~~, the possibilities are one~~include 1~~ head at

8   high data density and seven~~7~~ heads at low data density, two~~2~~ heads at high data

9   density and six~~6~~ heads at low data density, three~~3~~ heads at high data density

10   and five~~5~~ heads at low data density, four~~4~~ heads at high data density and four~~4~~

11   heads at low data density, one~~1~~ head at low data density and seven~~7~~ heads at

12   high data density, two~~2~~ heads at low data density and six~~6~~ heads at high data

13   density, and three~~3~~ heads at low data density and five~~5~~ heads at high data

14   density~~, etc~~. T~~Hence, t~~he format optimizer 66 considers all the combinatorial

15   possibilities, ~~and~~ in each case solves a constrained optimization problem and

16   ~~finally~~ chooses the ~~best~~ optimal solution amongst ~~all~~ the possibilities.

17   Alternatively, the format optimizer 66 can ~~be designed to~~ reach the ~~best~~ optimal

18   solution more directly by ~~solving a~~ (non-linear) mixed- integer programming.

19

20   Therefore, once the 1-D, 2-D and 3-D ~~joint~~ BPI distribution/~~frequency~~

21   ~~capability~~ CDFs ~~(discussed above)~~ at a ~~given~~ target performance metric are

22   ~~calculated and~~ passed ~~as input~~ to the format optimizer 66, the format optimizer

23   66 solves ~~the above~~ two problems, ~~namely:~~ (1) maximizing or improving the ~~drive~~

24   yield ~~(i.e.,~~ due to the target ~~pre-selected~~ performance metric~~, e.g., off-track SER)~~

25   while meeting the ~~a~~ desired nominal storage ~~drive~~ capacity, and (2) maximizing

26   the storage ~~disk-drive~~ capacity while meeting the~~a~~ desired nominal ~~drive~~ yield.

27

28   The format optimizer 66 ~~then~~ mathematically casts these two problems

29   ~~stated above~~ as constrained optimization problems and solves them using well-

30   known optimization techniques such as a ~~e.g.~~ line search algorithm. The

31   constrained optimization problems can also be cast as (non-linear) mixed-integer

1 programming and solved using existing ~~methods in~~ optimization methods~~theory~~.

2 Example constraints to be considered, and cast mathematically within the format

3 optimizer 66, include not exceeding a certain frequency at the outer diameter ~~OD~~

4 due to ASIC data rate limitations or at the inner diameter ~~ID~~ due to

5 head/disk~~media~~ limitations. Furthermore, closed form equations are derived and

6 used in the format optimizer 66 to estimate the storage capacity and ~~actual drive~~

7 yield ~~and drive capacity~~. The format generator 66 also considers ~~A Format~~

8 ~~Generator process, described below, is utilized to calculate the actual drive~~

9 ~~capacity after including all~~ possible overheads, such as adding ~~and including~~

10 redundant bits due to error correction coding or gray coding.

11

12 The format optimizer 66 also uses ~~the~~ information from the format

13 generator 68, such as the calculated format efficiency per zone (~~i.e.,~~ defined in

14 percentages as the amount of user data ~~e.g.~~ in blocks that can fit in all tracks in a

15 zone), or the number of tracks per zone, to achieve a very close estimate of the

16 storage ~~disk drive~~ capacity ~~calculation as~~ determined by the format generator 68.

17 Then, the format optimizer 66 calculates optimal linear bit density format profiles

18 as well as the optimal number of heads allocated to each vertically zoned format

19 profile.

20

21 For ~~As an~~ example, histograms are extracted and the corresponding BPI

22 distributions are estimated for different zones at the ~~desired~~ target on-track

23 symbol error rates ~~(e.g., for Zone1 at a target error rate of 1e⁻⁶, Zone2 at a target~~

24 ~~error rate of 1e⁻⁶, Zone3 at a target error rate of 1e⁻⁶, etc.) as described above~~of

25 $6x10^{-7}$. A format design is provided for a disk drive with four4 -heads ~~disk drives~~

26 (~~H~~and two frequencies to optimize yield =4), ~~and 2 vertical frequency~~

27 ~~format/profiles (F=2), wherein the disk drive yield is optimized~~ while meeting a

28 ~~minimum~~ storage capacity ~~requirement~~.

29

30 ~~Without the method of the present invention (vertical zoning),~~

31 ~~conventionally when the same frequency is used per head per zone, if one of the~~

1 ~~4 heads is a weak performing head having an error rate measurement e.g. 1e^{-5}~~

2 ~~at Zone1 (higher than the target error rate), that disk drive is failed. With the~~

3 ~~application of the present invention in that case, the format optimizer allocates~~

4 ~~the 3 other heads to higher frequencies, and allocates the weak head to a lower~~

5 ~~frequency at Zone1. The recording/playback performance of the weak head is~~

6 ~~compensated for, such that the minimum capacity requirement is met. As such,~~

7 ~~the format optimizer 66 utilizes the performance distributions to determine two or~~

8 ~~more optimal frequencies per zone, and the optimal number of head allocations~~

9 ~~to those frequencies per zone such that constraints such as required disk drive~~

10 ~~yield and/or capacity are met.~~

11

12 For example, the format optimizer 66 uses the ~~estimated~~ 1D, 2D and 3D

13 ~~joint frequency/~~BPI ~~capability~~ distributions at the ~~a desired~~ target performance

14 metric to jointly optimize for vertically zoned frequency format profiles and the

15 corresponding number of head allocations three zones at a time. An advantage

16 of considering three zones instead of one zone~~, as compared to only one~~ (and

17 thus ~~considering a~~ joint optimization instead of~~versus~~ individualized

18 optimization~~,~~) is that the joint optimization allows the ~~optimization of format~~

19 ~~profiles (e.g.,~~ frequency profiles to be optimized) across the stroke on each disk

20 surface. Therefore, joint optimization ~~in this way we~~ exploits the potential

21 correlation in performance from one zone to another zone as well as their

22 individual and weighted contribution to the storage ~~overall surface~~ capacity. A

23 joint optimization ~~approach~~ is preferable for a high/low~~/high~~ data density format

24 ~~layout~~ across the stroke for either improving the ~~drive~~ yield while keeping the

25 same storage~~drive~~ capacity~~,~~ or improving the storage ~~drive~~ capacity while

26 preserving the ~~same drive~~ yield.

27

28 The format optimizer 66 generate~~d results from the format optimizer~~s

29 ~~include:~~ the target high/low BPI formats per zone, the ~~(optimal)~~ number of head

30 allocations per format~~,/layout~~ and an estimate of the storage capacity and ~~drive~~

31 yield~~ and capacity~~. The accuracy of the estimates can be sensitive to the

1 underlying extracted (joint) BPI distributions at the target performance metrica

2 given (on or off-track) error rate. Further, the target high/low BPI formats can be

3 sensitive to the variance of the (extracted) BPI distributions. And, the variance of

4 the BPI distributions can be sensitive to the absolute value of the target

5 performance metric and the type of target performance metric(on or off-track)

6 target error rate and the choice of metric (e.g. error rate vs. MSE). In addition,

7 because the design of target high/low BPI formats are designed performed three

8 zones at a time and the yield improvement (while preserving the storage same

9 overall drive capacity) is based on the profile of the target nominal formats._;

10 Tthe format optimizer 66 also allows for a smoothing operation in order to smooth

11 the target variable BPI format designs if so desired. The format generator 68

12 determines the number of tracks per zone, the number of blocks per track, the

13 radius at each zone, as well as block and track format efficiency. _This

14 information is saved in e.g. output files for use with the format optimizer 66. The

15 format optimizer 66 then saves the design of target high/low BPI formats per

16 zone that it generates, in two separate files that can be read and loaded as input

17 files into the format generator 68.

18

19   Once the target format profiles are calculated, if they are non-smooth

20 across the stroke, optionally a smoothing process is applied. The format profiles

21 are then loaded into the format generator 68 described below, to create vertically

22 zoned formats and configuration pages. The formats and configuration pages

23 are used by the disk drive firmware to create binary files to be loaded inento the

24 reserve image of the disk drives as part of the file system. FIG. 2A shows the

25 communication between the format optimizer 66 and the format generator 68. In

26 this fashion, the design and implementation of the format profiles, as well as the

27 number of optimal head allocations are performed off-line and are predetermined

28 for every disk drive configuration.

29

30   For An example, in a disk drive with four heads and four disk surfaces on

31 two disks, the format optimizer 66 designs of format optimization for designing

1   vertically zoned <u>high and</u> low ~~and high~~ frequency profiles ~~for disk drives with 4~~

2   ~~heads (i.e., Head1 through Head4 corresponding to Surface1 through Surface 4~~

3   ~~of Disk1 and Disk2) is described.~~ <u>E</u>~~In this example,~~ every disk surface is

4   ~~(uniformly)~~ partitioned into three zones across the stroke, <u>at a track density</u> with a

5   fixed number of tracks ~~(TPI)~~ per zone, vertically aligned from one <u>disk</u> surface to

6   another. The nominal <u>disk</u> surface <u>data storage</u>~~capacity~~ ~~(~~before the ~~application~~

7   ~~of~~ vertical zoning~~)~~ can be approximated by the sum over all <u>the</u> zones of the

8   ~~products of~~ nominal tracks per zone <u>multiplied</u> by the nominal <u>BPI</u> ~~frequency~~ per

9   <u>track</u>~~zone~~ <u>multiplied</u> ~~and~~ by the format efficiency per zone. -Format efficiency per

10   zone is <u>the</u>~~a~~ percentage of ~~all~~ the user data that is effectively stored per zone.

11   T~~Then~~ the nominal <u>storage</u> ~~disk drive~~ capacity is ~~equal to~~ the nominal <u>disk</u>

12   surface <u>data storage</u>~~capacity~~ multiplied by the total number of <u>disk</u> surfaces (or

13   heads). The nominal number of tracks per zone and the format efficiency per

14   zone can be generated <u>by</u> ~~and obtained from~~ the format generator 68~~(described~~

15   ~~further below)~~.

16

17   Performing vertical zoning to ~~e.g.~~ improve the ~~drive~~ yield without losing

18   a<u>storage</u> ~~ny nominal (disk drive)~~ capacity~~,~~ finds the best frequency per zone and

19   per head such that the disk drive meets performance and <u>storage</u> capacity

20   requirements. I<u>As such,</u> if a disk drive with <u>four</u>4 heads fails ~~test process~~

21   ~~performance limits~~ due to <u>the</u> ~~e.g.~~ performance of <u>h</u>Head<u>_</u>1 at <u>z</u>Zone<u>_</u>1, but <u>the</u>

22   <u>performance of another head/zone pair, such as h</u>Head<u>_</u>1 at <u>z</u>Zone<u>_</u>2 ~~(or another~~

23   ~~head such as~~ <u>h</u>Head<u>_</u>3 at <u>z</u>Zone<u>_</u>1<u>,</u> ~~) performance~~ is significantly better<u>,</u> ~~(i.e.,~~

24   passing the test ~~limits~~ with reasonable margins~~)~~, then a higher <u>than nominal</u>

25   frequency ~~than nominal~~ at <u>z</u>Zone<u>_</u>1~~2~~ or <u>z</u>Zone<u>_</u>2~~1~~ is designed for <u>the strong</u>

26   heads ~~that are stronger (i.e. high density heads),~~ and ~~instead~~ the frequency at

27   <u>z</u>Zone<u>_</u>1 for <u>the weak</u> heads ~~that are weaker (i.e. low density heads)~~ is lowered.

28   This trade<u>_</u>off ~~is performed~~ <u>obtains a vertically zoned design of variable</u>

29   <u>frequencies per zone</u> such that the <u>storage</u> ~~overall disk drive~~ capacity is

30   preserved~~, to obtain a vertically zoned design of variable frequencies per zone~~.

31   In addition, the number of heads ~~(e.g.~~ per zone~~)~~ allocated to high or low <u>data</u>

1   density is determined. ~~_~~Thus, the storage ~~disk drive~~ capacity can be

2   approximated by the sum ~~(~~over all the zones~~)~~ of ~~the products of~~ the number of

3   strong ~~low density~~ heads ~~per zone~~ multiplied by the high~~low~~ frequency data

4   storage per zone multiplied by the format efficiency per zone plus the ~~(~~sum over

5   all the zones of ~~the) products of~~ the number of weak ~~high density~~ heads ~~per zone~~

6   multiplied by the low~~number of high~~ frequency data storage~~heads~~ per zone

7   multiplied by the format efficiency per zone.

8

9   For example, t~~In one version, the format optimizer solves for the above~~

10   ~~problem as follows.~~ The format optimizer 66 is provided with joint ~~the~~ BPI ~~(joint)~~

11   ~~frequency capability cumulative~~ distribution~~ functions (extracted and estimated~~

12   ~~from all heads considered in the measurement process above)~~ at the ~~a~~ desired

13   target performance metric ~~(i.e., the same targets used in the test process)~~. Then,

14   for every combinatorial possibility of head allocation ~~(e.g.~~ to high or low

15   frequency~~,)~~ the format optimizer 66 searches through a continuous range of

16   possible frequencies~~,~~ by considering every zone independently ~~(i.e.~~ using the

17   marginal distributions~~)~~ and by the combination of zones ~~(i.e.~~ using the joint BPI

18   distributions~~),~~ to maximize the ~~disk drive~~ yield calculated using a closed form

19   equation, such that the storage ~~disk drive~~ capacity after the ~~application of~~ vertical

20   zoning is applied is essentially the same as the nominal storage ~~disk drive~~

21   capacity. Further, the ~~(optimal)~~ high and low ~~and high~~ frequency profiles for

22   every combination of head allocations is compared and the one that results in the

23   highest ~~value of (calculated) disk drive~~ yield is chosen and passed to the format

24   generator 68 for the generation of vertically zoned configuration pages to be

25   used by the disk drive firmware.

26

27   The disk surfaces ~~of disks~~ can be partitioned into more than ~~the example~~

28   three zones ~~above~~. ~~The above steps of determining the optimal variable~~

29   ~~frequencies per zones are useful to consider more than three zones.~~ To reduce

30   computational complexity and time, if the selected/designed number of zones per

31   disk surface ~~in a disk drive~~ is more than three, the format optimizer 66 can ~~be~~

1   ~~used to~~ generate high and low ~~and high~~ frequency profiles three zones at a time

2   and~~,~~ ~~suitable smoothing operations are used to~~ smooth the profile after post-

3   processing. Another approach includes embedding the smoothing operator in

4   the design and extending the joint optimization to all the zones ~~so as~~ to consider

5   the ~~effect and~~ impact of smoothing to ~~drive~~ yield ~~(calculation)~~ as part of the

6   design rather than the later stages.

7

8   In the disk drive with four ~~above 4~~ heads ~~disk drive example~~, the ~~disk drive~~

9   yield is maximized while preserving the ~~same~~ nominal storage ~~disk drive~~

10   capacity. To determine the number of head allocations, the format optimizer 66

11   begins with one weak ~~one low density~~ head and three strong ~~high density~~ heads

12   ~~(e.g.,~~ per zone~~)~~. The format optimizer 66 searches through a continuous range

13   of possible frequency capabilities per zone, as well as two and three zones at a

14   time, by considering ~~and using~~ the 1D ~~(i.e., marginal)~~, ~~(joint)~~ 2D and 3D BPI

15   distributions that result in the best calculated ~~value of the drive~~ yield such that a

16   minimum nominal storage ~~drive~~ capacity can be obtained. Next, the format

17   optimizer 66 uses two weak heads and two strong ~~low and high density~~ heads

18   and repeats solving the ~~same~~ constrained optimization problem. This process is

19   continued until all the combinatorial possibilities are considered. Finally, the

20   format optimizer 66 chooses the solution that results in the best ~~calculated value~~

21   ~~of the drive~~ yield and provides the target high and low ~~and high~~ ~~(optimal)~~ data

22   density format profiles and the associated number of high and low head

23   allocations to the format generator 68. The format generator 68 then generates

24   vertically zoned format files and configuration pages to be used by the disk drive

25   firmware.

26

27   Format Generator

28   ~~In one embodiment, the format generator process block 68 is used for~~

29   ~~embedded servoing (i.e., servo position is generated by reading back written~~

30   ~~information from the disks, such as servo wedges in which position information is~~

43

1 ~~embedded on the disks, and that information is used to position the head on the~~

2 ~~disk surfaces).~~

3

4   T~~For example,~~ the format generator 68 ~~described herein~~ generally

5 performs three functions_. First, the format generator 68 uses_~~including utilizing~~

6 target formats/frequencies (or linear densities/BPI) for each zone ~~as an input,~~

7 and ~~performing an exact~~ calculat_es_~~ion of~~ the _data storage_ ~~capacity~~ of each zone

8 and _thus_ the _storage capacity of the_ disk drive ~~itself~~. Second~~Further~~, the format

9 generator 68 calculates the format efficiency (_the_ percent of the disk _surface_ ~~area~~

10 that is occupied by _user_ ~~customer~~ data) for each zone. Third,~~The third, and~~

11 ~~primary purpose of~~ the format generator 68 ~~is to~~ generate_s_ configuration page_s_

12 ~~data~~. The configuration pages contain per-drive, per-zone, and per-head-per-

13 zone parameters that are programmed into _the_ disk drive electronics _such as_

14 ~~components. Such components include~~ the _preamplifier 21, the_ ~~disk controller,~~

15 ~~the~~ read/_write_ channel _51~~,~~_ and the _controller 57_~~preamplifier~~. The parameters are

16 ordered such that the disk drive firmware selects the correct set of parameters to

17 be programmed into each of the components for the particular head and zone

18 that is being written to or read from at the time.

19

20   The format generator 68 calculates the ~~exact~~ frequency and the _data_

21 _storage_ ~~exact capacity~~ of each zone taking into consideration limitations in the

22 programmability _and_ ~~of the components and limitations of~~ the capabilit_y_~~ies~~ of _the_

23 disk drive components. _For example,_~~Some examples of component limitations~~

24 ~~include:~~ _the heads 16 have varying down-track separation between the read and_

25 _write elements, the preamplifier 21 has a minimum and maximum delay in turning_

26 _on the write current, the_ read/_write_ channel _51_ synthesizer frequencies are

27 limited to ~~a~~ discrete ~~collection of~~ frequencies_, the motor driver 53 can keep the_

28 _spindle motor 14 within a finite precision of the nominal rotational speed.~~;~~_

29 ~~preamplifier (not shown) has a minimum and a maximum delay in turning on its~~

30 ~~write current; the down-track separation between the head read and write~~

31 ~~elements (not shown) varies from component to component; the reference~~

1   ~~crystal (not shown) has finite accuracy and stability over temperature; the~~

2   ~~spindle motor driver can keep the spindle motor speed within a finite precision of~~

3   ~~the nominal rotational speed;~~ the controller 57 has specific latencies in

4   generating commands to the preamplifier 21 and the read/write channel 51 ~~and~~

5   ~~preamplifier,~~ often with a finite uncertainty as to the exact timing of these

6   commands, and a reference crystal (not shown) has finite accuracy and stability

7   over temperature, ~~etc~~.

8

9   The format generator 68 can be fully automated, or can be directed by a

10 human operator~~specialist~~. In the absence of input from the format optimizer 66,

11 the target per-zone BPI/frequency profiles, in particular, must be generated

12 by ~~from~~ a human operator~~input~~. In general, the human operator~~specialist~~

13 modifies the target frequency profiles until the desired storage capacity is

14 reached.

15

16 T ~~In one embodiment,~~ the format generator 68 includes a format efficiency

17 process that uses the format optimizer 66's target high/low~~/high~~ variable BPI

18 format designs as well as the optimal predetermined number of high/low~~/high~~

19 performing head allocations, to modify and generate the appropriate

20 configuration pages ~~(i.e.,~~ as part of the file system~~)~~. For each zone, the format

21 generator 68 selects the nearest frequency to the target frequency for that zone,

22 given the component limitations ~~and programmability~~ mentioned above. The

23 nearest frequency provide~~comprise~~s the target formats.

24

25 The optimal predetermined number of ~~low/~~high/low performing head

26 allocations comprises the number of heads allocated to each of the multiple

27 frequencies in each zone. The format optimizer 66 determines the head

28 allocation, which is input to the format generator 68. The capacity of a zone

29 depends ~~both~~ on the target frequencies and the number of heads allocated to

30 each frequency.

31

1 The format optimizer 66 uses the nominal average BPI or frequency

2 (nominal BPI format target designs) (e.g., one read/write frequency) in each zone

3 ~~as input~~ from the format generator 68 to estimate the ~~disk drive~~ yield before

4 applying the variable BPI designs. For a design with multiple frequencies per

5 zone, this is the weighted average ~~(by the number of allocated heads)~~ of the

6 multiple frequencies. The nominal format is created by ~~e.g.~~ a human operator

7 working with the format generator 68 in an~~the~~ interactive manner ~~described~~

8 ~~above~~.

9

10 The format generator 68 ~~performs~~ calculat~~e~~ions the~~of~~ number of tracks

11 per zone, number of blocks per track, radius at each zone as well as block and

12 track format efficiency to calculate the ~~drive~~ zone data storage~~capacity~~. ~~-~~The

13 format optimizer 66 estimates the zone data storage ~~capacity~~ using the tracks

14 per zone, radii, and format efficiency. Thus, the format optimizer 66 and the

15 format generator 68 interact as shown in FIG. 2A~~6~~. For example, in a disk drive

16 with four ~~for 4~~ head~~s disk drives~~, and two~~2~~ data density format frequency profiles

17 (~~i.e.,~~ high and low frequency profiles) with three~~3~~ zones across the disk surface,

18 after the measurement and optimization processes, the format generator 68 is

19 provided with two ~~2~~ optimal frequency profiles and the optimal allocation of the

20 heads. The format generator 68 then calculates the storage capacity, and if the

21 disk drive ~~capacity~~ meets the minimum required storage~~required~~ capacity, ~~then~~

22 the format generator 68 generates the configuration ~~files/~~pages for the disk drive

23 firmware. The configuration pages are used by the disk drive firmware to

24 command the head to write at an assigned frequency to a zone. If the calculated

25 storage ~~drive~~ capacity does not meet the minimum required storage capacity, the

26 format optimization is performed again with new format efficiency values~~,~~ and the

27 process is repeated.

28

29 Head ~~format~~ Aassignments ~~and selection criterion~~

30 Allocating ~~The process for allo~~the ~~cation of~~ numbers of heads to ~~each of~~

31 the predetermined multiple frequencies in a zone, and assigning ~~the process of~~

1   ~~assignment of~~ a particular head in a particular disk drive to a <u>particular</u>

2   frequency, are distinct. <u>T</u>~~First~~ the allocation ~~process is~~ performed by the format

3   optimizer 66<u>,</u> and applies to <u>the</u> disk drives of a particular design ~~(product)~~.

4   The<u>n,</u> ~~the~~ head assignment<u>s</u> <u>are</u>~~process is~~ <u>then</u> performed during manufacturing

5   as part of a test process undergone by each disk drive to be produced. ~~This~~

6   ~~section describes the assignment process task.~~

7

8   Once the configuration pages are generated and converted to binary files

9   as part of the file system, they can be loaded ~~and saved~~ int<u>o</u> a reserved image of

10 the disk drive for use after power cycling. Then, for every disk drive, the

11 ~~following example~~ assignment<u>s</u> <u>are</u>~~process is~~ performed per head and per zone<u>,</u>

12 to ~~determine~~ assignment ~~of~~ a ~~certain~~ predetermined number of heads to high BPI

13 formats and the remaining heads to low BPI formats in a <u>two</u>~~2~~ frequency design,

14 to satisfy <u>the</u> allocation of heads to <u>the</u>~~said~~ formats by the format optimizer 66.

15

16   The <u>head</u> assignment<u>s</u> ~~process~~ for the <u>two</u> ~~example 2~~ frequency format

17 where high and low frequencies are used<u>,</u> includes the steps of:

18   <u>(</u>1<u>)</u>~~.~~   Load default parameters from the configuration pages, and

19 calibrate selected parameters on a per head, per zone basis (e.g., load high BPI

20 format profile for all <u>the</u> zones across the stroke);

21   <u>(</u>2<u>)</u>~~.~~   Take measurements from <u>the</u>~~all~~ heads at ~~all~~ the disk surfaces at

22 pre-selected zones with respect to a <u>target performance</u> metric<u>,</u> ~~e.g., mean~~

23 ~~square error, on/off track error rate, etc.~~;

24   <u>(</u>3<u>)</u>~~.~~   For each head in every measured zone, sort/rank the heads by the

25 <u>target</u> performance metric from best to worst<u>,</u>~~;~~ select a pre-specified (by the

26 allocation process in the format optimizer 66) number of heads with the best

27 performance, and assign those heads to the high~~er~~ frequency for a particular

28 zone;

29   <u>(</u>4<u>)</u>~~.~~   Optionally interpolate between the measurements obtained from

30 the pre-selected number of zones to find the results for the other zones, and do

31 the same for the interpolated zones. The interpolation ~~operation in a version of~~

1 the present invention reduces the test process time. Head performances are

2 measured, sorted and assigned to a frequency for a subset of the total number of

3 zones. For the remaining zones, the heads are assigned by interpolating on the

4 head assignments made from the measurements;

5   (5).   For every zone, save the worst pre-specified number of weak bad

6 (i.e. low-performing) heads with respect to the target performance selected

7 metric; and

8   (6).   For every zone, load and calibrate all the weak bad heads with the

9 lower BPI format.

10

11   The above process can be used to improve storage yield, improve

12 capacity, improve yield and trade-off between yield and storage capacity and

13 yield. In a test, the heads can be passed or failed with respect to a target

14 performance metric (e.g., off track error rate) to determine if the test target limits

15 are met.

16

17   The disk driveservo firmware is extended to load more than one format

18 profile. A head can be assigned a different read/write frequency per zone across

19 a disk surface, and radially similarly situated zones on different disk surfaces can

20 have different read/write frequencies assigned to the corresponding heads

21 whereby one head is assigned a different frequency/format profile than another

22 head.

23

24   The head example aassignments process described herein applyies to a

25 format design with two recording frequencies per zone, but. However, the

26 process can be easily extended to more than two frequencies per zone and ,

27 wherein the process can be iterated upon to assign heads to more than two

28 frequencies per zone, as described by an example below. For example, in a

29 design with H heads and F frequencies per zone, above steps 1 and 2 are

30 completed for the high frequency. The first selection of heads in step 3 assigns

31 the highest h1 heads, where h1 is the pre-specified number of heads allocated to

1 the highest frequency for that zone. The remaining (H -- h1) heads are then

2 loaded and calibrated with the second highest frequency (step 1 again),

3 measurements are taken (step 2 again), and the heads are ordered relative to

4 the metric and the best h-2 heads are assigned to the second highest frequency

5 (step 3 again). Here h-2 is the pre-specified number of heads allocated to the

6 second highest frequency in the zone. Steps 1-3 of the process are then iterated

7 for the (H -- h-1 -- h-2) heads, followed by the (H -- h1 -- h2 -- h3) heads, and

8 so on, until hF heads remain to be assigned to the lowest frequency. -The set of

9 {h1 . . ., ..., hF} heads receive comprise the head allocation made by the format

10 optimizer 66.

11

12 Table 1 below illustrates the result of an example of the vertical zoning

13 head assignments process on a disk drive with six6 heads and five5 zones

14 across the stroke on each disk surface. Each head is assigned to either a high

15 or low data density format based on record/playback performance of that head,

16 and wherein as discussed above, the number of heads assigned to high data low

17 density and the number of heads assigned to low data high density is according

18 to the head allocation results determined by the format optimizer 66.

19

HEAD #	FORMAT\ZONE ZONE 1	ZONE 2	ZONE 3	ZONE 4	ZONE 5
0	Low	High	Low	High	Low
1	High	Low	High	High	Low
2	High	Low	High	Low	High
3	High	High	Low	High	High
4	Low	High	High	High	High
5	High	High	High	Low	High

20

21 Table 1 – EAn example for the format assignment of a disk drive after test

22 process, using vertical zoning with variable BPI across the zones.

23

24

1   ~~FIGs. 3-6 show example steps of an embodiment of the above processes.~~

2   ~~Referring to~~ FIG. 3 shows, a flowchart of ~~n example~~ vertical zoning data

3   collection that~~process~~ includes the steps of:

4   (1)   Select a number of disk drives for data measurement/collection

5   ~~process~~ (step 300);

6   (2)   Create a nominal linear bit density profile KFCI (~~i.e.,~~ nominal

7   _KFCI):

8         $$\overline{kFCI}(R),$$ wherein R is the disk radius (step 302);

9

10   (3)   Create more linear bit density profiles by multiplying the nominal

11   _KFCI by the scaling factor x_i, (step 304):

$$(1 \pm x_i) * \overline{kFCI}(R)$$

12

13   (4)   Create a binary file system for every generated profile (step 306)~~,~~

14   ~~i.e. for~~

15

$$i \in \{1, \cdots, N\}$$

16

17   wherein N is the total number of frequency format profiles~~,~~ ~~f~~For

18   example, for N = 2, having X_1, and X_2, if $X_1 = 0.05$ and $X_2 = 0.1$, then including

19   the nominal frequency format ~~itself,~~ there are five~~5~~ different frequency profiles in

20   step 304~~,~~ as follows: (a) nominal_KFCI, (b) 1.05 x *~~-~~nominal_KFCI, (c) 0.95 x *

21   nominal_KFCI, (d) 1.1 x *~~-~~nominal_KFCI, and (e) 0.90 x *~~-~~nominal_KFCI ~~(wherein~~

22   ~~"*" is the multiplication operator)~~;

23   (5)   Select the first head by setting i to 1(step 308);

24   (6)   Load the file system i i~~o~~nto the reserved image of the disk drives

25   (step 310);

26   (7)   Take the head performance measurements ~~(e.g., (on/off) track MSE~~

27   ~~and SER measurements)~~ (step 312);

28   (8)   Unload and save the results in the dData bBase (step 314);

1   (9)   Increment i by one ~~($i=i+1$)~~ (step 316);

2   (10)   Determine if ~~is~~ i = N? ~~(~~step 318)~~)~~;

3   (11)   ~~————————~~If not, go to step ~~-~~310; and

4   (12)   Otherwise, ~~else~~ stop (step 320)~~done~~.

5

6   The above process collects performance data for all the heads at all the

7   zones.

8

9   ~~Referring to~~ FIG. 4 shows~~,~~ a flowchart of ~~n example~~ vertical zoning post-

10   measurement ~~processing~~ and per zone BPI distribution extraction that ~~process~~

11   includes the steps of:

12   (1)   Organize the head performance data ~~(e.g., MSE and SER)~~

13   ~~obtained above,~~ for every head $i \in \{1, \cdots, M_1\}$ and every zone $j \in \{1, \cdots, M_2\}$ as

14   a function of the linear bit density samples, ~~wherein in this example~~ M_1 is the total

15   number of heads in the disk drives selected for ~~the~~ measurement ~~process (e.g.,~~

16   ~~40 disk drives each including 4 heads, results in total of M1=160 heads),~~ and M_2

17   is the total number of zones, to generate head performance histograms (step

18   400);

19   (2)   Choose a target performance metric ~~(e.g., MSE or SER)~~ (step 402);

20   (3)   Set $j = 1$ and $i = 1$ (step 404);

21   (4)   Interpolate/eExtrapolate BPI at the ~~specified~~ target performance

22   metric ~~(e.g., MSE or SER)~~ for head i at zone j (step 406);

23

24   (5)   Select the next head by incrementing i by one ~~($i = i + 1$)~~ (step 408);

25

26   (6)   Determine if ~~Is~~ $i = M_1$? ~~(i.e., have~~ all the heads have been

27   processed~~?)~~ by determining if $i = M_1$ (sStep 410);

28

1   (7)   If not, go~~t~~ to step 406 to process the next head, <u>otherwise</u>~~else~~

2   generate <u>a</u> frequency capability histogram at ~~that given~~ zone j for all the heads

3   (step 412);

4

5   (8)   <u>Determine if</u> ~~Is $j = M_2$? (i.e., have~~ all <u>the</u> zones <u>have</u> been

6   processed~~?)~~ <u>by determining if $j = M_2$</u> (<u>s</u>~~S~~tep 414);

7

8

9   <u>   </u>~~(9)   If yes, stop;~~

10

11   ~~(9~~<u>10</u>~~)~~ <u>If not,</u> ~~Otherwise,~~ move to the next zone and start with the first head

12   again, <u>set</u> ~~whereby~~ $j = j + 1$ <u>and,</u> $i = 1$ (step 416)~~,~~ and go to step 406<u>; and</u>

13   <u>(10)   Otherwise, stop (step 418)</u> ~~to repeat~~.

14

15   The above process generates ~~(1D)~~ frequency capability histograms at a

16   target performance metric ~~and~~ for every zone by considering all the heads from

17   the sample disk drives selected <u>for</u> ~~in the~~ measurement ~~process~~. Using the ~~(1D)~~

18   frequency capability histograms at a ~~given~~ target performance metric, ~~techniques~~

19   ~~in~~ probability theory known to those skilled in the art can be adopted to estimate

20   the ~~(1D)~~ frequency capability distributions. Further, the above proce<u>ss</u>~~dure~~

21   ~~above~~ is extended ~~(i.e.,~~ by using 2D and 3D interpolation/extrapolation routines~~)~~,

22   to extract and estimate the 2D and 3D joint frequency capability histograms and

23   their associated distributions.

24

25   ~~Referring to~~ FIG. 5 <u>shows,</u> a <u>flowchart of head assignments for N heads</u>

26   <u>with</u> ~~n example head assignment process for~~ a two frequency format (~~N=2,~~

27   high/low <u>data</u> density) <u>that</u> ~~design,~~ includes the steps of:

28   (1)   Assign all ~~n~~ <u>the</u> heads in a disk drive to the ~~first selected format~~

29   ~~(e.g.,~~ high <u>data-</u> density format~~)~~ (step 500);

30   (2)   Calibrate all ~~n~~ <u>the</u> heads at <u>the</u> high <u>data</u>-density format for

31   selected zones (step 502);

1   (3)   Measure <u>the head</u> performance metric at <u>the</u> selected zones for all

2 <u>the</u>n heads (step 504);

3   (4)   For each selected zone, rank <u>the</u> heads by <u>the head performance</u>

4 metric (step 506);

5   (5)   For each selected zone, assign <u>the</u> highest K heads to <u>the</u> high

6 <u>data</u> -density format, <u>and assign the</u> other <u>N</u>n-K heads to <u>the</u> low <u>data</u> density

7 <u>format</u> (step 508);

8   (6)   Optionally interpolate <u>the</u> head assignment<u>s</u> for <u>the</u> remaining

9 zones (step 510); and

10   (7)   Complete <u>the</u> calibration of all <u>the</u> heads and all <u>the</u> zones at <u>the</u>

11 assigned formats (step 512).

12

13   The above process completes <u>the</u> assignment of each head in each disk

14 drive to a predetermined frequency.

15

16   <u>T</u>~~As shown in FIG. 2A, information is passed between the format~~

17 ~~generator 68 and the format optimizer 66, wherein initially,~~ the format generator

18 68 passes <u>the</u> ~~information including e.g.~~ track format<u>s</u>~~layout~~ to the format

19 optimizer 66 to have a more accurate way of calculating <u>the storage</u> capacity

20 (nominal format). Such information and constraints are provided to the format

21 optimizer 66 to solve <u>the</u>~~said~~ joint optimization problems. The format optimizer

22 66 performs a coarse -calculation of <u>the storage</u> capacity, whereas the format

23 generator 68 performs an exact calculation of <u>the storage</u> capacity. The format

24 generator <u>68</u> ~~performs functions of~~ provid<u>es</u>~~ing~~ format information (<u>such as</u> ~~e.g.,~~

25 number of tracks per zone, and <u>the</u> zone format~~layout~~) to the format optimizer 66,

26 and calculat<u>es</u>~~ing~~ <u>the</u> exact storage~~format~~ capacity. Such information is passed

27 once from the format generator 68 to the format optimizer 66 for a <u>head</u> design

28 ~~(e.g., 4 head design)~~ <u>with a given number of heads</u>. -The format generator 68

29 initially provides nominal information- to the format optimizer 66, <u>and</u> ~~wherein~~ the

30 format optimizer 66 performs its calculation of target densities (zone frequencies

31 and number of heads allocated to each frequency) and provides that information

1   to the fFormat -gGenerator 68. The format generator 68 then determines if

2   required storage capacity has been reached. Adjusting the target densities to

3   meet storage capacity and/or yield and/or capacity requirements includes

4   adjusting the selected zone density or zone frequencies.

5

6   Referring to FIG. 6 shows , a flowchart of format generation and

7   optimization in which an in example Format Generator/Format Optimizer

8   Iterativeon process for a minimum storage capacity requirement (C), and a user

9   specified storage allowed overcapacity Delta, (Δ) includes the steps of:

10   (1)   Determine the disk geometry, track density (TPI) and servo

11   spokewedge details, and provide the output inner diameter (ID) and outer

12   diameter (OD) radii,; the track density (TPI),; the number of servo spokwedges,

13   and the servo spokewedge length (step 600);

14   (2)   The fformat generator 68 generates the initial format at the storage

15   capacity using the values ID and ,-OD radii, the TPI, the number of servo

16   spokwedges and the servo spoke wedge length, and provideoutputs the radius of

17   each zone per disk surface, the number of tracks per zone, the number of blocks

18   per track, and the format efficiency by zone (step 602);

19   (3)   The fformat optimizer 66 generates optimal target densities at all

20   the zones using the radius of each zone per disk surface, the number of tracks

21   per zone, the number of blocks per track, and the format efficiency by zoneas

22   described above, and provides the high and low BPI outputs frequency density

23   targets (e.g., low/high BPI) by zone, and the number of high and low BPI

24   frequency density (e.g., low/high BPI) head allocations by zone (step 604);

25   (4)   The fformat generator 68 generates new formats with a storage

26   cCapacity (thei.e., number of logical blocks per disk drive) (step 606);

27   (5)   Determine iIf the storage cCapacity > C and the storage cCapacity

28   < (C + ΔDelta) (step 608);

29   ____(6)   If not, , then stop;

30   ——(6)   Otherwise, adjust the target densities (sStep 610), and go to step

31   606; and

1   (7)   Otherwise, stop (step 612).

2

3   For ~~In one~~ example, the disk surface capacity is ~~described by the~~

4 ~~equation:~~ TPI x BPI x (1 + ECC) / FE, ~~wherein~~ TPI is the track density, BPI is the

5 linear bit density, ECC is the fractional level of error correcting code ~~used~~ which

6 is typically about 0.1, and FE is the format efficiency which is typically about 0.57.

7

8   The above process completes the format generation ~~process~~.

9

10   As another example ~~scenario of the results generated by an embodiment~~

11 ~~of vertical zoning according to the present invention~~, a set of thirty-two ~~32~~

12 ~~matured~~ disk drives are selected and ~~wherein~~ each disk drive includes twelve ~~12~~

13 heads. The 1D, 2D and 3D ~~joint~~ BPI ~~empirical~~ distributions are extracted at an

14 ~~given specified target~~ on-track symbol error rate from the ~~three pre-specified~~

15 ~~radial zones, i.e.,~~ outer, middle and inner zones. Next, the BPI ~~extracted~~

16 distributions are fed ~~into~~ the format optimizer 66, and high or low ~~or high~~

17 frequency per zone format designs are obtained at the three ~~specified~~ zones.

18 This is performed once by individual optimization, ~~all~~ based on 1D BPI

19 distributions at each of the three zones, and once by joint optimization based on

20 the measurements obtained from the three zones and their extracted 1D, 2D and

21 3D BPI distributions. The head format allocation search ~~process (VZ test)~~ is

22 performed by ~~in a~~ simulation, and ~~wherein~~ for each zone the one-format designs

23 ~~(i.e.~~ before the application of vertical zoning~~)~~ are a special case of the two-format

24 variable BPI designs by forcing the high and low ~~and high~~ formats to be ~~the same~~

25 ~~and~~ equal to the nominal BPI format at that zone. Furthermore, the pass/fail of

26 the disk drives is ~~decided~~ based on ~~the criterion that~~ each head at every zone

27 passing a target ~~given~~ on-track symbol ~~target~~ error rate as well as off-track

28 squeeze and un-squeeze offset margins. Then, the ~~drive~~ yield is calculated

29 by ~~(i.e., in~~ simulation by interpolation/extrapolation of the measurement data~~)~~

30 before and after the application of vertical zoning (VZ). ~~The following~~ Table 2

31 summarizes the results:

	Using Joint Optimization	Using Individual Optimization
Drive Yield (Yd)	93.75	90.625
Drives failed after VZ	4 & 29	4, 6 & 29
Drives recovered	2, 3, 13, 19, 21 & 25	2, 3, 13, 19, 21 & 25
Passed drives failed after VZ	None	6
Drives failed before VZ	2, 3, 4, 12, 19, 21 & 29	2, 3, 4, 12, 19, 21 & 29
	i.e., drive yield before VZ	i.e., dDrive yield after VZ
	Yd=75%	Yd = 75%

<u>Table 2</u>

In addition to disk drives, the present invention is useful with other storage devices such as e.g. tape drives, optical drives, etc. A ItThough a manufacturing test case for a two format design is illustratedescribed, the search algorithm can be easily be generalized to a higher number of formats. The design of two formats based on 1D, 2D and 3D joint storage density BPI distributions can easily be generalized to higher order or dimensions by considering more zones than three zones. The design of format designs can be generalized from two to a higher number of formats. The measurement procedure can be generalized to consider more zones as well as off-track measurements such as 747 curves or quality metrics versus error rate measurements to perform a correlation study for the choice of best metric with the leastss potential test time.

Further, the above methods for a per zone variable BPI design can be easily extended to a variable BPI/TPI design as described below. The measurement process is extended to further include 747 measurements of all the heads from a pre-selected number of disk drives. To speed up the measurements of raw data, instead of 747 measurements, off-track and adjacency margin (squeeze measurements) of theall heads can be performed. Once the 747 raw data of theall heads at a pre-selected number of zone locations is determined, for every zone, (joint) BPI/TPI distributions can be extracted at the given desired target(s) by post-measurement data processing of data. The choice of a target is an integral part of the amount of performance gain, such as disk drive yield, due to the per zone variable BPI/TPI designs. Some example choices of target(s) are off-track symbol error rate, the variance

56

1   ~~of~~ position error signal <u>variance, and</u> ~~or even~~ a combination of both. After the

2   joint BPI/TPI distributions are extracted and available for <u>the</u>~~all~~ zones, a per zone

3   variable BPI/TPI design can be obtained by solving two<u>-</u>constrained (joint)

4   optimization problems: one that maximizes the ~~drive~~ yield while keeping the

5   same <u>disk</u> drive areal density<u>,</u> and another that maximizes the <u>disk</u> drive areal

6   density while keeping the same ~~drive~~ yield. Once the per zone variable BPI/TPI

7   designs are obtained, ~~a head BPI/TPI allocation and selection criterion, similar to~~

8   ~~that described herein, can be used such that~~ a pre-selected number of heads are

9   allocated to high and low density BPI and TPI formats, for example, for ~~the case~~

10   ~~of~~ <u>a</u> two variable BPI/TPI per zone design performed as part of <u>the</u> test process.

11

12   The present invention improves <u>storage capacity</u> ~~drive yield and drive~~

13   ~~capacity~~ (and <u>or</u> ~~consequently areal density at a fixed target BPI)</u> <u>and yield</u>~~,~~ and

14   ~~allows~~ reduc<u>es</u>~~ing~~ the target TPI by increasing the average BPI across the stroke

15   per head (depending on the number of formats considered) to meet a desire

16   <u>storage</u> ~~target drive~~ capacity. In particular, ~~due to a maximum deliverable data~~

17   ~~rate of the ASIC components (e.g., channel, controller and preamp)~~ the BPI at

18   the outer diameter may be limited by the <u>maximum</u>~~minimum~~ deliverable data rate

19   of the ~~mentioned~~ ASIC components. ~~-~~For example, if the controller <u>57 has</u>~~is~~

20   ~~capable of~~ <u>a</u> maximum deliverable data rate of 650 MHz, the preamp<u>lifier 21</u>

21   <u>has</u>~~capable~~ <u>a maximum deliverable data rate</u> of 700 MHz and the <u>read/write</u>

22   channel <u>51 has</u>~~capable~~ <u>a maximum deliverable data rate</u> of 750 MHz, then the

23   BPI at the outer diameter is limited by the controller <u>57</u> at a maximum deliverable

24   data rate of 650 MHz. Thus, a conventional one format BPI profile across the

25   stroke does not achieve the desired <u>storage</u> ~~drive~~ capacity and ~~the desired~~

26   ~~manufacturing drive~~ yield~~. The target BPI is increased and the BPI profile across~~

27   ~~the stroke is relaxed, wherein according to~~ <u>whereas</u> the present invention~~, the~~

28   per zone variable BPI ~~design can be used to design (variable BPI)~~ target formats

29   ~~that~~ meet the desired <u>storage</u> ~~drive~~ capacity at a fixed target TPI while improving

30   the ~~overall drive~~ yield.

31

1 ~~Referring back to FIG. 2A and FIGs. 3-6, in one embodiment of the~~

2 ~~present invention, the steps of the example method of the present invention: (1)~~

3 Tthe data ~~collection/~~measurer~~ment process block~~ 62~~,~~ can be implemented by ~~on~~

4 a general purpose comput~~ering equipment~~ 61~~, known in the art,~~ and the drive

5 electronics of the disk drive 100. The general purpose computer 61 can be a

6 high end PC, a PC server or a workstation and include programmable simulation

7 software. The drive electronics can include~~including~~ the ~~special purpose~~

8 ~~electronic circuit (e.g.,~~ logic ~~circuit)~~ 49 and the controller ~~on board~~

9 ~~microprocessor~~ 57. T~~he~~ logic ~~(FIG. 1B), configured according to the present~~

10 ~~invention, wherein the special purpose electronic~~ circuit 49 ~~is configured to~~

11 performs the measurements and~~,~~ the controller~~on board microprocessor~~ 57

12 directs the logic ~~special purpose~~ circuit 49~~,~~ and transfers the data to the general

13 purpose computer 61. T~~, (2)~~ the head assignments ~~process~~ can be implemented

14 by~~on~~ the controller ~~on board microprocessor~~ 57 with ~~within the disk drive 100~~

15 ~~configured according to the present invention,~~ the ~~wherein a~~ data collection sub-

16 task ~~is related to the head assignment task such that the data collection sub-task~~

17 ~~is~~ performed by the logic~~special purpose electronic~~ circuit 49 ~~within the disk drive~~

18 ~~100.~~ The ~~, (3) the~~ steps in each of ~~the~~ post-measurement data ~~-~~ process~~oring~~

19 ~~block~~ 64, the format optimizer ~~block~~ 66 and the format generator ~~block~~ 68 can be

20 implemented by~~on~~ the general purpose comput~~ering equipment~~ 61 ~~(e.g., high~~

21 ~~end PC, PC server or workstation, etc., including programmable simulation~~

22 ~~software) configured according to the present invention.~~

23

24 The present invention has been described in considerable detail with

25 reference to certain preferred versions thereof; however, other versions are

26 possible. Therefore, the spirit and scope of the appended claims should not be

27 limited to the description of the preferred versions contained herein.

1 ## Abstract

2 A method of defining ~~such~~ a storage format in ~~multiple~~ data storage

3 devices,~~-~~ each data storage device having <u>multiple</u> ~~a plurality of~~ storage media

4 and ~~a plurality of~~ corresponding ~~data transducer~~ heads, each ~~transducer~~ head for

5 recording on and playback of information from a corresponding storage medi<u>a</u>~~um~~

6 in at least one zone, ~~wherein~~ <u>and</u> each zone includ<u>ing</u>~~es a plurality of~~ concentric

7 tracks for recording on and playback of information. <u>_</u>The method includes ~~the~~

8 ~~steps of:~~ selecting <u>a sample of the</u>~~a plurality of said~~ data storage devices<u>,</u>~~;~~ for

9 each selected data storage device~~,~~ measuring a record/playback performance

10 capability of each head at one or more read/write frequencies per zone<u>,</u>~~; based~~

11 ~~on said performance capability measurements,~~ generating storage density

12 distributions corresponding to ~~at least a number of~~ the heads in <u>the</u>~~said~~ selected

13 data storage devices <u>based on the performance capability measurements,</u>~~;~~

14 selecting a group of read/write frequencies for <u>the</u>~~said multiple~~ data storage

15 devices <u>with,</u>~~;~~ two or more frequencies for each zone~~,~~ based on <u>the</u>~~said~~ storage

16 density distributions<u>,</u>~~;~~ and assigning one of <u>the</u>~~said~~ read/write frequencies to

17 each head based on <u>the</u> performance capability of that head.

1   **SUBSTITUTE SPECIFICATION UNDER 37 C.F.R. 1.125**

2

3   **Per Zone Variable BPI for Improving Storage Device Capacity and Yield**

4   By

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6   Mathew Vea

7   And

8   George Iszlai

9

10   <u>**Field of the Invention**</u>

11   The present invention relates to information storage on a storage media

12   such as a disk in a disk drive.

13

14   <u>**Background of the Invention**</u>

15   Data storage devices such as disk drives are used in many data

16   processing systems. Typically a disk drive includes a magnetic data disk having

17   disk surfaces with concentric data tracks, and a transducer head paired with

18   each disk surface for reading data from and writing data to the data tracks.

19

20   Disk drive storage capacity increases by increasing the data density (or

21   areal density) of the data stored on the disk surfaces. Data density is the linear

22   bit density on the tracks multiplied by the track density across the disk surface.

23   Data density is measured in bits per square inch (BPSI), linear bit density is

24   measured in bits per inch (BPI) and track density is measured in tracks per inch

25   (TPI). As data density increases, the head performance distribution also

26   increases which diminishes disk drive storage capacity and yield.

27

28   Conventional disk drives fail to account for the different capabilities of the

29   head and disk surface pairs. Conventionally, each disk surface is formatted to

30   store the same amount of data as every other disk surface. However, each head

31   and disk surface pair has unique data recording capability, such as sensitivity

1 and accuracy, which depends on the fly height of the head over the disk surface,

2 the magnetic properties of the head and the quality/distribution of the magnetic

3 media for the disk surface. Thus, in conventional disk drives a head and disk

4 surface pair that has a low error rate is formatted to the same BPI and TPI as a

5 head and disk surface pair that has a high error rate.

6

7 Conventional disk drive manufacturing applies a single error rate and a

8 single data storage level for the head and disk surface pairs, and scraps disk

9 drives that include a low performing head and disk surface pair that fails to meet

10 the qualifying requirements. This lowers storage capacity due to inefficient use

11 of high performing head and disk surface pairs that can store more data, and

12 lowers yield due to disk drives being scrapped if they include a low performing

13 head and disk surface pair even if they also include a high performing head and

14 disk surface pair.

15

16 U.S. Patent Nos. 6,091,559 and 5,596,458 provide different BPI on

17 different disk surfaces, however these approaches do not take into consideration

18 multiple constraints, including head performance across the stroke per disk

19 surface, performance requirements such as throughput and manufacturing

20 requirements such as test time. Instead, disk surface zone frequencies are

21 selected based on a single metric for one head.

22

23 There is, therefore, a need for storing data in a disk drive which improves

24 disk drive storage capacity and yield and accounts for head performance

25 variation.

26

27 **Summary of the Invention**

28 The present invention satisfies this need.

29

1   In an embodiment, a variable BPI storage format is a function of zones in

2   data storage devices, such as disk drives, based on head performance variation

3   between different heads in a set of data storage devices.

4

5   In another embodiment, a population of disk drives is selected, and head

6   performance measurements are taken for disk surface locations at different

7   frequencies. Head performance distributions obtained from the head

8   performance measurements provide storage formats for the disks by determining

9   different read/write frequencies for the zones, and the heads in each disk drive

10   are assigned to the frequencies.

11

12   The head allocations and assignments are per head per zone, taking into

13   consideration head performance variation across the zones. For instance, if a

14   first head performs well at the inner diameter (ID) of the disk but poorly at the

15   outer diameter (OD) of the disk, and a second head has reverse performance,

16   then the first head is assigned a high BPI at the ID and a low BPI at the OD, and

17   the second head is assigned in the opposite fashion. The per zone variable BPI

18   storage format improves storage capacity by taking several manufacturing and

19   customer constraints into consideration. Performance of each head across the

20   stroke of the disk surface, as well as performance variation from one head to

21   another, determines the storage format and the head assignments.

22

23   In another embodiment, the head performance and the storage format are

24   determined off-line at development/design time, and then the heads are assigned

25   to the different frequencies at manufacturing time. For example, the storage

26   format for each zone and the number of heads allocated to each data density are

27   preselected at design time, and then the heads are assigned to high/low data

28   density storage formats at manufacturing time.

29

30   In another embodiment, a method defines the storage format in data

31   storage devices, with each data storage device having multiple storage media

3

1   and corresponding heads, each head for recording on and playback of

2   information from a corresponding storage media in multiple zones, and each

3   zone including concentric tracks for recording on and playback of information.

4   The method includes (1) selecting a sample of the data storage devices, (2) for

5   each selected data storage device, measuring a record/playback performance of

6   each head at one or more read/write frequencies per zone, (3) generating head

7   performance distributions based on the head performance measurements, (4)

8   selecting a group of read/write frequencies for the data storage devices, two or

9   more frequencies for each zone, based on the head performance distributions,

10   and thereafter, during manufacturing, (5) assigning one of the read/write

11   frequencies to each head based on the performance of that head.

12

13   Advantageously, the present invention provides consistent performance

14   (both sequential and random throughput) across a population of disk drives,

15   improves storage capacity and yield and reduces test time.

16

17   **Brief Description of the Drawings**

18   These and other features, aspects and advantages of the present

19   invention will become understood with reference to the following description,

20   appended claims and accompanying figures where:

21   FIG. 1A shows a disk drive with a data storage format;

22   FIG. 1B shows drive electronics for the disk drive;

23   FIG. 1C shows servo tracks and data tracks on a disk surface;

24   FIG. 1D shows a zone format in the disk drive with N disks, 2N heads and

25   different heads in a zone on different disk surfaces;

26   FIG. 1E shows another zone format on a disk surface;

27   FIG. 1F shows zones on a disk surface that each include virtual cylinders;

28   FIG. 1G shows a data track format for the virtual cylinders in a zone on

29   different disk surfaces with corresponding heads;

30   FIG. 1H shows a servo track and data track format for a zone on different

31   disk surfaces with corresponding heads in which the number of servo tracks and

1   data tracks in different virtual cylinders of a zone on different disk surfaces are

2   the same;

3   FIG. 1I shows another servo and data track format that varies from zone

4   to zone on a disk surface;

5   FIG. 2A shows a function and flow diagram for generating the format of

6   FIG. 1A;

7   FIG. 2B shows a graph of playback error measurement for a head at a

8   zone at different recording frequencies;

9   FIG. 2C shows a histogram of the frequency capabilities of the heads in a

10   set of disk drives at a zone at a fixed target error rate;

11   FIG. 2D shows a joint BPI distribution;

12   FIG. 3 shows a flowchart of vertical zoning data collection in FIG. 2A;

13   FIG. 4 shows a flowchart of vertical zoning and per zone joint BPI

14   distribution extraction in FIG. 2A;

15   FIG. 5 shows a flowchart of head assignments in FIG. 2A; and

16   FIG. 6 shows a flowchart of format generation and optimization in FIG. 2A.

17

18   **Detailed Description of the Invention**

19   Data storage devices used to store data for computer systems include, for

20   example, disk drives, floppy drives, tape drives, optical and magneto-optical

21   drives and compact drives. Although the present invention is illustrated by way

22   of a disk drive, the present invention can be used in other data storage devices

23   and other storage media, including non-magnetic storage media, is as apparent

24   to those of ordinary skill in the art and without deviating from the scope of the

25   present invention.

26

27   FIGs. 1A-1C show a hard disk drive 100 diagrammatically depicted for

28   storing user data and/or operating instructions for a host computer 54. The disk

29   drive 100 includes an electro-mechanical head-disk assembly 10 that includes

30   one or more rotating data storage disks 12 mounted in a stacked, spaced-apart

1 relationship upon a spindle 13 rotated by a spindle motor 14 at a predetermined

2 angular velocity.

3

4   Each disk 12 includes at least one disk surface 23, and usually two disk

5 surfaces 23 on opposing sides. Each disk surface 23 has associated magnetic

6 media for recording data. The spindle motor 14 rotates the spindle 13 to move

7 the disks 12 past the magnetic transducer heads 16 suspended by the

8 suspension arms 17 over each disk surface 23. Generally, each head 16 is

9 attached to a suspension arm 17 by a head gimbal assembly (not shown) that

10 enables the head 16 to swivel to conform to a disk surface 23. The suspension

11 arms 17 extend radially from a rotary voice coil motor 20. The voice coil motor

12 20 rotates the suspension arms 17 and thereby positions the heads 16 over the

13 appropriate areas of the disk surfaces 23 in order to read from or write to the disk

14 surfaces 23. Because the disks 12 rotate at relatively high speed, the heads 16

15 ride over the disk surfaces 23 on a cushion of air (air bearing).

16

17   Each head 16 includes a read element (not shown) for reading data from a

18 disk surface 23 and a write element (not shown) for writing data to a disk surface

19 23. Most preferably, the read element is a magneto-resistive or giant magneto-

20 resistive sensor and the write element is inductive and has a write width which is

21 wider than a read width of the read element.

22

23   Each disk surface 23 is divided into concentric circular data tracks 30 that

24 each have individually addressable data sectors 35 in which user data is stored

25 in the form of magnetic bits. The data sectors 35 are separated by narrow

26 embedded servo sectors 25 arranged in radially extending servo spokes. The

27 servo sectors 25 include a series of phase-coherent digital fields followed by a

28 series of constant frequency servo bursts. The servo bursts are radially offset

29 and circumferentially sequential, and are provided in sufficient numbers that

30 fractional amplitude read signals generated by the head 16 from portions of at

31 least two servo bursts passing under the head 16 enable the controller 57 to

1   determine and maintain proper position of the head 16 relative to a data track 30.

2   A servo burst pattern for use with a head that includes a magneto-resistive read

3   element and an inductive write element is described by commonly assigned U.S.

4   Patent No. 5,587,850 entitled "Data Track Pattern Including Embedded Servo

5   Sectors for Magneto-Resistive Read/Inductive Write Head Structure for a Disk

6   Drive" which is incorporated herein by reference.

7

8   The controller 57 controls the heads 16 to read from and write to the disk

9   surfaces 23. The controller 57 preferably is an application specific integrated

10 circuit chip (ASIC) which is connected by a printed circuit board 50 to other

11 ASICs, such as a read/write channel 51, a motor driver 53 and a cache buffer 55.

12 The controller 57 preferably includes an interface 59 which connects to the host

13 computer 54 via a known bus 52 such as an ATA or SCSI bus.

14

15 The controller 57 executes embedded or system software including

16 programming code that monitors and operates the disk drive 100. During a read

17 or write operation, the host computer 54 determines the address where the data

18 is located in the disk drive 100. The address specifies the head 16, the data

19 track 30 and the data sector 35. This data is transferred to the controller 57

20 which maps the address to the physical location in the disk drive 100, and in

21 response to reading the servo information in the servo sectors 25, operates the

22 voice coil motor 20 to position the head 16 over the corresponding data track 30.

23 As the disk surface 23 rotates, the head 16 reads the servo information

24 embedded in each servo sector 25 and also reads an address of each data

25 sector 35 in the data track 30.

26

27 During a read operation, when the identified data sector 35 appears under

28 the head 16, the entire contents of the data sector 35 containing the desired data

29 is read. In reading data from the disk surface 23, the head 16 senses a variation

30 in an electrical current flowing through the read element when it passes over an

31 area of flux reversals on the disk surface 23. The flux reversals are transformed

1 into recovered data by the read/write channel 51 in accordance with a channel

2 algorithm such as partial response, maximum likelihood (PRML). The recovered

3 data is then read into the cache buffer 55 where it is transferred to the host

4 computer 54. The read/write channel 51 most preferably includes a quality

5 monitor which measures the quality of recovered data and provides an indication

6 of the data error rate. One channel implementation which employs channel error

7 metrics is described in commonly assigned U.S. Patent No. 5,521,945 entitled

8 "Reduced Complexity EPR4 Post-Processor for Sampled Data Detection" which

9 is incorporated herein by reference. The present invention uses the indication of

10 recovered data error to select linear bit density, track density and/or error

11 correction codes.

12

13   During a write operation, the host computer 54 remembers the address for

14 each file on the disk surface 23 and which data sectors 35 are available for new

15 data. The controller 57 operates the voice coil motor 20 in response to the servo

16 information read back from the servo sectors 25 to position the head 16, settles

17 the head 16 into a writing position, and waits for the appropriate data sector 35 to

18 rotate under the head 16 to write the data. To write data on the disk surface 23,

19 an electrical current is passed through a write coil in the inductive write element

20 of the head 16 to create a magnetic field across a magnetic gap in a pair of write

21 poles that magnetizes the disk surface 23 under the head 16. When the data

22 track 30 is full, the controller 57 moves the head 16 to the next available data

23 track 30 with sufficient contiguous space for writing data. If still more track

24 capacity is required, another head 16 is used to write data to a data sector 35 of

25 another data track 30 on another disk surface 23.

26

27   The present invention increases the storage capacity and yield of data

28 storage devices, such as the disk drive 100, having magnetic media surfaces,

29 such as the disk surfaces 23.

30

31

1 <u>Vertical Zoning</u>

2   In every disk drive, there is a distribution associated with the head and

3 disk surface pair performance. The present invention takes advantage of that

4 distribution to determine different linear bit density (BPI) recording frequency

5 assignments for the heads, and optionally track allocation.

6

7 A set of disk drives is selected, and head performance measurements are taken

8 for each selected disk surface location in the disk drives at different frequencies.

9 Empirical frequency capability histograms are extracted at a target performance

10 metric from the measurement data. Head performance distributions (such as

11 joint BPI distributions) are estimated from the histograms and fed into a format

12 optimizer to obtain and design vertically zoned frequency format profiles across

13 the stroke and the disk surface as well as the optimal number of head allocations

14 to the frequencies. Once the frequency format profiles and the optimal number

15 of head allocations are determined, during a test process, every head at every

16 zone is assigned to one of the frequencies based on the head's performance.

17

18   FIG. 1A shows a storage format for the disk drive 100. Each disk surface

19 23 includes zones 60 that extend from one radius of the disk 12 to another radius

20 of the disk 12, and the format of the zones 60 on each disk surface 23 is the

21 same. The variable BPI storage format is a function of the zones 60 on each

22 disk surface 23 based two data recording formats -- high data density and low

23 data density -- that use (1) head performance variation from one head 16 to the

24 next head 16 in the disk drive 100, and (2) the performance variation of a given

25 head 16 across the stroke of a disk surface 23.

26

27   The disk drive 100 includes the disks 12 depicted as disks 1 to N, the

28 heads 16 depicted as heads 1 to 2N, and the disk surfaces 23 depicted as disk

29 surfaces 1 to 2N. Each disk 12 includes two opposing disk surfaces 23, and

30 each head 16 is associated with one of the disk surfaces 23. For instance, head

31 1 is associated with disk surface 1 of disk 1, head 2 is associated with disk

1   surface 2 of disk 1, head 3 is associated with disk surface 3 of disk 2, and head

2   2N is associated with disk surface 2N of disk N.

3

4   Each disk surface 23 includes the zones 60 depicted as zones 1 to M

5   across its stroke, with zone 1 at the ID and zone M at the OD. The radial

6   boundaries on zone 1 of disk surface 1 of disk 1 are the same as the radial

7   boundaries of zone 1 on disk surface 2 of disk 1, and so on. Similarly, the radial

8   boundaries of zone M on disk surface 1 of disk 1 are the same as the radial

9   boundaries of zone M on disk surface 2 of disk 1, and so on. However, different

10   zones 60 across the stroke on each disk surface 23 need not necessarily have

11   the same number of data tracks 30 or TPI. For example, zone 1 on disk surface

12   1 of disk 1 has the same number of data tracks 30 and the same radial

13   boundaries as zone 1 on disk surface 1 of disk N, and zone M on disk surface 1

14   of disk 1 has the same number of data tracks 30 and the same radial boundaries

15   as zone M on disk surface 1 of disk N. However, the number of data tracks 30 in

16   zones 1 and M can be different.

17

18   Each disk surface 23 also includes virtual cylinders 39 depicted as virtual

19   cylinders 1 to n. Each zone 60 includes multiple virtual cylinders 39, and each

20   virtual cylinder 39 includes multiple data tracks 30 on each disk surface 23.

21   Further, within a virtual cylinder 39, different heads 16 may read and write at

22   different frequencies (variable BPI) to provide vertical zoning.

23

24   FIG. 1C shows the data tracks 30 and the servo tracks 37 on the disk

25   surface 23. The data tracks 30 include the data sectors 35, and the servo tracks

26   37 include the servo sectors 25. Five servo tracks 37 depicted as servo tracks

27   Sa, Sb, Sc, Sd and Se are shown in relation to three data tracks 30 depicted as

28   data tracks Tk1, Tk2 and Tk3.

29

30   The servo tracks 37 are written on the disk surface 23 during

31   manufacturing at a servo track density that is about 150% of the maximum data

1. track density. The servo track density is determined by the maximum read width

2. and the minimum write width of a population of the heads 16. After writing the

3. servo tracks 37 at the servo track pitch, the data tracks 30 can be written at any

4. radial position between the servo tracks 37. The data track density (TPI) can be

5. selected from predetermined levels or can be based on the location of a data

6. sector 35. Additional tests can be performed to determine the optimum data

7. track density of the disk surface 23. Each servo track 37 comprises radially

8. similarly situated servo sectors 25 in the servo spokes. For example, the servo

9. track Se contains servo sectors 25 at essentially the same radial distance from

10. the center of the disk 12, the servo track Sd contains servo sectors 25 at

11. essentially the same radial distance from the center of the disk 12, etc.

12.

13. FIGs. 1D to 1I show vertical zone formats in which different heads 16 on

14. different disk surfaces 23 may read/write at different linear frequencies (variable

15. BPI) on the data tracks 30 within a virtual cylinder 39.

16.

17. FIG. 1D shows a zone 60 format of the disk drive 100 with N disks 12, 2N

18. heads 16 and different heads 16 in zone 1 on different disks 12. FIG. 1E shows

19. another zone 60 format on the disk surface 23. FIG. 1F shows each zone 60 on

20. the disk surface 23 includes multiple virtual cylinders 39. Zone 1 includes virtual

21. cylinders 1 to j, and zone M includes virtual cylinders 1 to i. The radial

22. boundaries of the zones 60 are shown as dark circles, and the radial boundaries

23. of the virtual cylinders 39 are shown as light circles. FIG. 1G shows a data track

24. 30 format for the virtual cylinders 39 in a zone 60 on different disk surfaces 23

25. with corresponding heads 16. FIG. 1H shows a data track 30 and servo track 37

26. format for a zone 60 on different disk surfaces 23 with corresponding heads 16 in

27. which the number of data tracks 30 and servo tracks 37 in different virtual

28. cylinders 39 of a zone 60 on different disk surfaces 23 is the same. FIG. 1I

29. shows a data track 30 and servo track 37 format for zones 60 on the disk surface

30. 23 with a corresponding head 16 in which the data track 30 and servo track 37

31. format varies from zone 1 to zone M.

1

2   <u>Format Optimization</u>

3   The vertical zoning includes designing, optimizing and selecting two or

4   more recording frequency profiles per zone for a sample number of disk drives

5   off-line during the disk drive development/design phase. Then, for a population

6   of disk drives, in each disk drive, each head is assigned to one of the

7   predetermined frequencies for a given zone during the disk drive manufacturing

8   phase. A predetermined read/write frequency (BPI) is assigned to each head

9   based on a known number of head allocations and the head's performance. A

10   head assigned to a high frequency records more bits on a track, and a head

11   assigned to a low frequency records less bits on a track.

12

13   Performance testing of the head and disk surface pairs occurs after full

14   read/write and servo calibration and optimization of the disk drive. If the tested

15   performance of head 1 at zone 1 on disk surface 1 of disk 1 at a given frequency

16   is better than a target performance metric, then head 1 is considered strong

17   since it is capable of storing more information than originally accounted for.

18   Thus, the recording frequency can be increased at zone 1 on disk surface 1 of

19   disk 1 for head 1 yet the performance does not fall below the target performance

20   metric. If the tested performance of head 2 at zone 1 on disk surface 2 of disk 1

21   at the same frequency is worse than a target performance metric, then head 2 is

22   considered weak but can be compensated for by relaxing the frequency at which

23   head 2 operates to ensure the target performance metric is met. Performing the

24   above trade-off between the heads for all the zones provides frequency profiles

25   across the stroke that are vertically zoned frequency format profiles without loss

26   of storage capacity.

27

28   Advantageously, by compensating for head 2, rather than failing the disk

29   drive due to head 2, the vertical zoning improves yield. Furthermore, the format

30   optimizer uses the head performance (read/write frequency capability)

31   distributions at every zone and a target performance metric to design a group of

1 read/write frequency format profiles for strong and weak heads within a given

2 disk drive. The format optimizer also determines the optimal number of strong

3 versus weak heads.

4

5 The format optimizer does not determine which specific head is at the high

6 or low frequency, but does provide a breakdown of the number of heads at the

7 high frequency and the number of heads at the low frequency. The breakdown is

8 fixed, performed off-line, and used during the head assignments. Then, in the

9 head assignments during a manufacturing test, out of 2N heads in a disk drive

10 with N disks, the number of heads assigned to each predetermined frequency is

11 determined.

12

13 The heads within a set of disk drives are allocated to the predetermined

14 group of read/write frequencies as part of the optimization process to meet the

15 storage capacity and yield requirements for the disk drives. The allocation

16 process allocates a number of the heads in a disk drive to the predetermined

17 frequencies, however the specific assignment of a particular head to a particular

18 frequency is performed later during the assignment process. For example, in a

19 two read/write frequency design (high frequency and low frequency) for a set of

20 disk drives each with eight heads, in each disk drive for zone 1 on all the disk

21 surfaces, any five of the eight heads are allocated to the high frequency and any

22 three of the eight heads are allocated to the low frequency based on the

23 performance measurements of the heads in the set of the disk drives.

24 Thereafter, the specific assignment of each particular head to a particular

25 predetermined frequency is performed. For example, in a first disk drive heads

26 2, 5, 6, 7, 8 are assigned to the high frequency and heads 1, 3, 4 are assigned to

27 the low frequency, whereas in a second disk drive heads 1, 4, 5, 6, 7 are

28 assigned to the high frequency and heads 2, 3, 8 are assigned to the low

29 frequency. The specific head assignments depend on the specific capability of

30 the heads in each disk drive.

31

1   The optimal number of heads per frequency is determined at the same

2   time that the group of read/write frequencies are selected by the format optimizer

3   by solving a joint constrained optimization problem. For example, in a disk drive

4   with eight heads and a high frequency and a low frequency that are each a

5   different ratio of a reference frequency, in each vertical zone, allocating two

6   heads to the high frequency and six heads to the low frequency provides a

7   specific storage capacity. Changing the frequency ratios and the number of

8   heads allocated to each frequency provides a different storage capacity. Thus,

9   the disk drive storage capacity is a function of the number of heads multiplied by

10   the frequency allocated to each head per zone. For example, if a nominal disk

11   surface data storage is 1 unit, and if the high frequency = 4/3 x the reference

12   frequency and the low frequency = 2/3 x the reference frequency, then one head

13   can be at the high frequency for every one head at the low frequency to maintain

14   the average disk surface data storage at 1 unit.

15

16   The head performance distributions represent percentages of the heads in

17   the disk drives than can operate at different frequencies. For example, the head

18   performance distribution is a BPI distribution that represents the head frequency

19   capability at a target performance metric. Using the head performance

20   distributions (the head read/write frequency capability distributions at the target

21   performance metric for every zone), the number of heads, the format of the

22   virtual cylinders and the desired storage capacity, the format optimizer

23   determines the frequency for each virtual cylinder in each zone and the number

24   of heads in each disk drive allocated to each frequency to achieve the desired

25   storage capacity. Thereafter, in the assignment process as part of testing each

26   disk drive, each head in a population of disk drives is assigned to one of the

27   predetermined frequencies based on the allocation criteria and the specific head

28   performance. For example, in a disk drive with four heads, the format optimizer

29   considers three heads at the high frequency and one head at the low frequency,

30   then two heads at the high frequency and two heads at the low frequency, and

31   then one head at the high frequency and three heads at the low frequency.

1   Thus, the format optimizer uses the head performance distributions to determine

2   the storage capacity and yield.

3

4   In one version of the optimization process, the yield is maximized while

5   meeting a constraint on storage capacity. In another version, the storage

6   capacity is maximized while meeting a constraint on yield. In the former case,

7   the format optimizer uses a format where the maximum number of disk drives

8   qualify and the fewest number of disk drives fail to reach the required storage

9   capacity. For example, in a disk drive with four heads and a nominal disk surface

10 data storage of 1 unit, allocating two heads to the high frequency and two heads

11 to the low frequency provides a nominal data storage of 4 units. In the later

12 case, the format optimizer uses a format where the maximum number of disk

13 drives reach the required storage capacity and the fewest number of disk drives

14 fail to qualify. For example, in a disk drive with four heads and a nominal disk

15 surface data storage of 1 unit, allocating three heads to the high frequency and

16 one head to the low frequency provides a high data storage of 4.66 units.

17

18   Thus, the vertical zoning for variable BPI includes an off-line

19 predetermined per zone format design based on disk drive data collection and

20 head performance distribution extraction. In one version, a fixed predetermined

21 zone boundary format is used to design multiple frequency BPI formats based on

22 representative or actual joint BPI distributions at one or more desired target

23 performance metrics (such as off-track symbol error rate) and the joint BPI

24 distributions are extracted from a finite preselected set of disk drives.

25

26   The collected data is used to extract the joint BPI distributions for the

27 heads at every preselected zone, and the per zone design of high and low data

28 density formats for the heads is performed off-line. The format optimizer solves a

29 constrained joint optimization off-line to obtain the format designs using well-

30 known constrained optimization routines. Using joint BPI distributions allows

31 consideration of potential correlation of BPI capability of the heads across the

15

1 stroke as well as the individual contribution of each head to the storage capacity

2 and yield.

3

4 The off-line format design allows the format optimizer to consider

5 additional constraints. For example, as more information is obtained in

6 quantifying the thermal stability constraints of the disks (which in turn places an

7 upper bound on linear bit density for the heads) the off-line format design does

8 not exceed these constraints. Likewise, if there are data rate constraints in either

9 the write process or the ASICs, such constraints may be cast within the joint

10 constrained format optimizer to ensure the constraints are not exceeded.

11

12 <u>Data Measurement</u>

13 A measurement procedure is used to collect data from which one-

14 dimensional (1D), two-dimensional (2D) and three-dimensional (3D) BPI

15 distributions at a desired read/write target error rate (or any other metric) can be

16 extracted. Data is collected based on head capability measurements taken at

17 different radial positions on the disk. The distributions represent the capability of

18 each head at different radial positions. For example, several disk drives which

19 collectively include 1000 heads are selected for measurement, and

20 record/playback error rate measurements of the 1000 heads from zone 1 to zone

21 24 of the disk surfaces at different frequencies are obtained. Thereafter, in post-

22 measurement data processing (a) the BPI capability of each head at a fixed

23 target performance metric at zone 1 is determined to obtain a 1D BPI distribution,

24 (b) the BPI capability of each head at a fixed target performance metric at zones

25 1 and 5 is determined to obtain a 2D BPI distribution, and (c) the BPI capability of

26 each head at a fixed target performance metric at zones 1, 5 and 20 is

27 determined to obtain a 3D BPI distribution.

28

29 The BPI distributions are then passed to the format optimizer to solve

30 three constrained optimization problems to provide head frequency per zone

31 allocations. The three constrained optimization problems (1) maximize the yield

1   while preserving the storage capacity, (2) maximize the storage capacity while

2   preserving the yield, and (3) maximize the yield while ensuring a target storage

3   capacity is met at a fixed target TPI. Customer related or ASIC data rate

4   constraints are also considered. The format optimizer can solve any of these

5   three problems, and one problem can take priority over another depending on the

6   process phase. For example, at an early development phase where the disk

7   drive components are not mature, meeting the storage capacity may be a

8   challenge. In that phase, the format optimizer can design the variable BPI format

9   profiles by solving the second problem. Then, as the disk drive components

10   mature, meeting the storage capacity becomes easier and meeting the yield

11   becomes more important, the first problem may be solved. Thereafter, as part of

12   a test process, an assignment algorithm ensures the appropriate head

13   assignments to the predetermined high and low data density formats per head

14   and per zone or across the stroke based on the head allocation breakdown of the

15   format optimizer.

16

17   The yield is improved while meeting the target storage capacity by

18   allowing a frequency format with high and low frequencies and a predetermined

19   number of high and low performing head allocations. Using realistic constraints

20   such as ASIC data rate limitations, the same fixed target TPI is maintained by

21   increasing the average target BPI across the stroke to achieve the target storage

22   capacity. As such, head performance variation from one head to the next head

23   in the disk drive and for the head across the stroke of the disk surface is used to

24   increase the storage capacity while preserving the yield. For example, the

25   vertical zoning format uses several design constraints to improve yield using a

26   variable high and low BPI design with a fixed predetermined number of head

27   allocations as a function of the zones while meeting the target storage capacity at

28   a fixed target TPI. The head performance variation or correlation across the

29   stroke is also used.

30

17

1   Further, the difference in data storage of two or mores zones on a disk

2   surface is considered as it affects storage capacity. The storage capacity is

3   defined as a weighted combination of the zone capacities across the stroke on

4   each disk surface in the disk drive. A correlation in the head performance

5   statistics is extracted from one head to another head, and for every head

6   considered in a set of disk drives across the stroke on each disk surface.

7

8   The joint constrained optimization determines a per zone target high and

9   low data density format. The optimization takes into account constraints

10   including customer related requirements such as minimum logical block count,

11   monotonic data rate, and maximum data rate at the outer zones which can be

12   formulated into additional constraints.

13

14   <u>Example Implementation</u>

15   FIG. 2A shows a function and flow diagram for generating the optimal data

16   density format shown in FIG. 1A. The function and flow diagram includes a data

17   measurer 62, a post-measurement data processor 64, a format optimizer 66 and

18   a format generator 68.

19

20   <u>Data Measurer</u>

21   The data measurer 62 takes data measurements for every zone at a finite

22   number of frequency samples.

23

24   The data measurer 62 implements a measurement procedure that

25   includes the steps of:

26   (1)   Create several different predetermined linear bit density format

27   profiles including a profile of different frequencies per zone across the stroke,

28   such as a first profile including high frequency 1 for zone 1, high frequency 2 for

29   zone 2 . . . high frequency M for zone M, and a second profile including low

30   frequency 1 for zone 1, low frequency 2 for zone 2 . . . low frequency M for zone

31   M to be loaded on a representative number of disk drives selected for the

1 measurement process (or if possible on all the available disk drives for that

2 build);

3   (2)   Load a frequency format profile;

4   (3)   Perform read/write and servo optimization and calibration;

5   (4)   Take head performance measurements including off-track mean

6 square error or quality metric and/or symbol error rate at preselected frequencies

7 for preferably all available zones and save the data; and

8   (5)   Repeat steps 2-4 for the remaining frequency format profiles.

9

10   The above steps are performed for the selected disk drives in the

11 measurement process.

12

13   Thus, in the disk drive 100, the data is recorded on a data sector 35 of the

14 disk surface 23 at the selected data density by positioning the head 16 abutting

15 the data sector 35 and sending the appropriate write signals to the head 16.

16 Typically, a sample of data is recorded on the disk surface 23 such that a

17 significant number of errors are detected (such as ten errors per error rate

18 measurement) to obtain a statistically representative sampling of the error rate

19 for the data sector 35. Thereafter, the recorded data is read by the head 16 and

20 stored by the host computer 54 for evaluation. An error rate of the recorded data

21 is measured or compiled by comparing the written data with the read data,

22 element-by-element. The error rate can be determined using a bit error

23 measurement in which a bit of data read from the disk surface 23 is compared

24 with the correct bit, a bit steam measurement in which a bit stream of data read

25 from the disk surface 23 is compared with a correct bit stream, or a mean square

26 error metric measurement in which a waveform read from the disk surface 23 is

27 compared with an ideal waveform to provide an error signal that is squared and

28 summed to form the error metric.

29

30   In this description, a component distribution is defined as a random

31 variation (tolerance) of a prespecified target nominal component parameter such

1　as a head write/read width, and a distribution is defined as a probability

2　distribution function. During the early product development, when the head

3　performance distributions are wide and unreliable, data from a mature set of disk

4　drives is used for extracting reference joint BPI distributions at a target

5　performance metric such as on-track symbol error rate, off-track symbol error

6　rate, on-track mean square error or off-track mean square error. Later, when the

7　head performance variation from one phase to the next in the distribution is

8　expected to be minimal, new sets of measurement data are collected using a

9　selected population of disk drives at their more mature stages.

10

11　　　　Thus, a number of BPI formats including the nominal target format are

12　selected. Then, on-track or off-track symbol error rate or mean square error

13　measurements are taken at different preselected locations of the disk surfaces,

14　such as the outer, middle and inner zones. The performance measurements can

15　be limited to these three zones to reduce the measurement time. However,

16　preferably the performance measurements over multiple zones and other

17　measurements such as off-track 747 can be performed. The nominal formats are

18　generated from the data.

19

20　　　　Two or more different linear bit density format profiles can be loaded at a

21　time. In one example, two variable BPI format per zone design (high and low

22　data density format profiles) can be created for measurement data collection

23　during every build. In this way, more statistical data can be collected from more

24　disk drives, however there will be only two frequency samples per zone available

25　for post-measurement data processing.

26

27　Post-Measurement Data Processor

28　　　　Post-measurement data processor 64 uses the available performance

29　metric measurements to calculate each head's frequency performance, for

30　instance as kilo flux per inch (kFCI) or kilo bits per inch (kBPI), at a target

1 performance metric. The performance of every head at every zone is determined

2 as a function of the read/write frequency profiles used for the measurements.

3

4 For example, if six different frequency profiles are used, then for every

5 head per zone, the data measurer 62 provides measured data as a function of

6 six frequency samples at a target performance metric. In the post-measurement

7 data processor 64, the measured data is sorted and the performance of every

8 head at every zone at the six frequency samples is extracted to generate

9 frequency capability histograms at a target performance metric.

10

11 FIG. 2B shows a graph of playback error measurement for a head at a

12 zone at different recording frequencies. The curve shows head performance as

13 a function of frequency (BPI). The x-axis is the read/write frequency in kBPI at

14 the outer diameter, and the y-axis is the on-track symbol error rate on a log

15 scale. Each frequency sample 70 is depicted as "+", each curve fit point 72 is

16 depicted as "o" and each projected frequency 74 is depicted as "◊".

17

18 In the illustration, head 1 at zone 1 in disk drive 3 is measured at six

19 frequency samples. The curve is generated using a least square polynomial fit to

20 the six frequency samples. The projected frequency (BPI) for a target on-track

21 symbol error rate is extracted from the curve by interpolation or extrapolation.

22 For example, if the target on-track symbol error rate is 10^{-8} then the projected

23 frequency is determined by interpolation, whereas if the target on-track symbol

24 error rate is 10^{-6} then the projected frequency is determined by extrapolation.

25 The on-track symbol error rate varies as a function of frequency and increases as

26 the frequency increases.

27

28 The nominal kBPI (before vertical zoning) and the kBPI gain relative to the

29 nominal kBPI are also shown. Head 1 can be classified as a strong head

30 because there is reasonably significant margin before its on-track symbol error

31 rate of –9.1 (log) at a nominal frequency/kBPI of ~ 188 can be changed to a

1   projected on-track symbol error rate of –6.22 at a frequency/kBPI of ~ 217.

2   Hence, there is a total kBPI gain of ~ 29, allowing the nominal frequency to

3   increase by 15% while meeting the target on-track symbol error rate performance

4   metric of 6×10^{-7}. Thus, head 1 of disk drive 3 has a frequency capability of about

5   217 at the target on-track symbol error rate of 6×10^{-7}, which provides a sample

6   for the generation of a histogram.

7

8   FIG. 2C shows a histogram of the frequency capabilities of the heads in a

9   set of disk drives at a zone at a target performance metric. The histogram 76 is

10 constructed using the projected frequencies determined in FIG. 2B for the heads

11 in the selected disk drives reading from zone 1 at the target on-track symbol error

12 rate of 6×10^{-7}. The x-axis is the projected frequency capability at the outer

13 diameter, and the y-axis is the number of heads. The histogram is extracted and

14 empirical, has a normal distribution fit and has a width that corresponds to the

15 head performance variation.

16

17   Additional histograms are constructed for the remaining zones based on

18 the frequency capabilities determined from the graphs based on the performance

19 measurements taken at the remaining zones so that every available head

20 considered in the disk drives under measurement has BPI histograms at a target

21 performance metric per zone.

22

23   Thus, performance measurements are provided for each head at each

24 zone in the selected disk drives, the graphs are generated for each head at each

25 zone, the frequency capabilities for each head at each zone are determined for a

26 target performance metric, and the histograms are constructed for each head at

27 each zone for the target performance metric. Likewise, if a histogram of head

28 BPI capability at a target performance metric of a zone (such as an intermediate

29 zone) is not available then the histogram for that zone can be constructed by

30 interpolation or extrapolation. The histograms can be used to estimate a BPI

31 distribution.

1

2   FIG. 2D shows a joint BPI distribution calculated from the histograms of

3   the heads in the measured disk drives at a target performance metric. The joint

4   BPI distribution is a 2D distribution based on the histograms in FIG. 2C at the

5   target on-track symbol error rate of 6×10^{-7}. The x-axis is the BPI capability of the

6   heads at the middle diameter (MD) of the disks, the y-axis is the BPI capability of

7   the heads at the outer diameter (OD) of the disks, and the z-axis is the calculated

8   number of heads divided by the total number of heads. The joint BPI distribution

9   provides an estimate of the probability that the heads meet the target

10   performance metric at the MD and the OD.

11

12   The joint BPI distribution may predict, for example, that 10% of the heads

13   in the measured disk drives can operate at a high frequency of 1.5 x the

14   reference frequency, 50% of the heads can operate at a high frequency of 1.25 x

15   the reference frequency, 90% of the heads can operate at the reference

16   frequency, and 99.9% of the heads can operate at a low frequency of 0.75 x the

17   reference frequency.

18

19   For example, the linear bit density sensitivity of every head at zone K

20   (where K ranges from 1 to M) at the six frequency samples is determined. If

21   frequency 1K, frequency 2K . . . frequency 6K are the frequency samples at zone

22   K, every head is positioned on the same track in zone K and the record/playback

23   performance of each head is measured at every frequency sample using a target

24   performance metric.

25

26   The BPI distributions can be calculated at the target performance metric

27   as ID, 2D or 3D distributions that are marginal, individual or per zone

28   distributions, respectively. The format optimizer uses the estimated frequency

29   capability BPI distributions for every zone at the target performance metric to

30   determine the storage capacity and yield.

31

1 <u>Format Optimizer</u>

2   The format optimizer 66 provides variable BPI optimization. The format

3 optimizer 66 solves three constrained optimization problems in response to

4 various inputs. The first problem maximizes the yield while preserving the

5 storage capacity, the second problem maximizes the storage capacity while

6 preserving the yield, and the third problem maximizes the yield while reducing

7 the track density and meeting the storage capacity. The inputs include the

8 number of different read/write frequencies (frequency profiles or formats), the

9 number of heads in each disk drive, the BPI distributions, and the nominal

10 storage capacity. The BPI distributions indicate the frequency capability

11 distribution of the heads at a target performance metric.

12

13 The format optimizer 66 simultaneously searches through a continuous range of

14 all possible frequency capabilities to maximize the yield such that the nominal

15 storage capacity is met. The format optimizer 66 can also perform the same

16 operation with the storage capacity and the yield interchanged.

17

18   The format optimizer 66 can optimize high and low data density as a

19 function of the zones. For example, in a disk drive with eight heads, the

20 possibilities are one head at high data density and seven heads at low data

21 density, two heads at high data density and six heads at low data density, three

22 heads at high data density and five heads at low data density, four heads at high

23 data density and four heads at low data density, one head at low data density

24 and seven heads at high data density, two heads at low data density and six

25 heads at high data density, and three heads at low data density and five heads at

26 high data density. The format optimizer 66 considers all the combinatorial

27 possibilities, in each case solves a constrained optimization problem and

28 chooses the optimal solution among the possibilities. Alternatively, the format

29 optimizer 66 can reach the optimal solution more directly by non-linear mixed-

30 integer programming.

31

1   Therefore, once the 1D, 2D and 3D BPI distributions at a target

2   performance metric are passed to the format optimizer 66, the format optimizer

3   66 solves two problems, (1) maximizing or improving the yield due to the target

4   performance metric while meeting the desired nominal storage capacity, and (2)

5   maximizing the storage capacity while meeting the desired nominal yield.

6

7   The format optimizer 66 mathematically casts these two problems as

8   constrained optimization problems and solves them using well-known

9   optimization techniques such as a line search algorithm. The constrained

10   optimization problems can also be cast as non-linear mixed-integer programming

11   and solved using existing optimization methods. Example constraints to be

12   considered, and cast mathematically within the format optimizer 66, include not

13   exceeding a certain frequency at the outer diameter due to ASIC data rate

14   limitations or at the inner diameter due to head/disk limitations. Furthermore,

15   closed form equations are derived and used in the format optimizer 66 to

16   estimate the storage capacity and yield. The format generator 66 also considers

17   possible overhead such as adding redundant bits due to error correction coding

18   or gray coding.

19

20   The format optimizer 66 also uses information from the format generator

21   68 such as the calculated format efficiency per zone (defined in percentages as

22   the amount of user data in blocks that can fit in all tracks in a zone), or the

23   number of tracks per zone, to achieve a very close estimate of the storage

24   capacity determined by the format generator 68. Then, the format optimizer 66

25   calculates optimal linear bit density format profiles as well as the optimal number

26   of heads allocated to each vertically zoned format profile.

27

28   For example, histograms are extracted and the corresponding BPI

29   distributions are estimated for different zones at the target on-track symbol error

30   rate of 6×10^{-7}. A format design is provided for a disk drive with four heads and

31   two frequencies to optimize yield while meeting storage capacity.

1

2   For example, the format optimizer 66 uses the 1D, 2D and 3D BPI

3 distributions at the target performance metric to jointly optimize for vertically

4 zoned frequency format profiles and the corresponding number of head

5 allocations three zones at a time. An advantage of considering three zones

6 instead of one zone, and thus joint optimization instead of individual optimization,

7 is that the joint optimization allows the frequency profiles to be optimized across

8 the stroke on each disk surface. Therefore, joint optimization exploits the

9 potential correlation in performance from one zone to another zone as well as

10 their individual and weighted contribution to the storage capacity. Joint

11 optimization is preferable for a high/low data density format across the stroke for

12 either improving the yield while keeping the same storage capacity or improving

13 the storage capacity while preserving the yield.

14

15   The format optimizer 66 generates the target high/low BPI formats per

16 zone, the optimal number of head allocations per format, and an estimate of the

17 storage capacity and yield. The accuracy of the estimates can be sensitive to the

18 underlying BPI distributions at the target performance metric. Further, the target

19 high/low BPI formats can be sensitive to the variance of the BPI distributions.

20 And, the variance of the BPI distributions can be sensitive to the absolute value

21 of the target performance metric and the type of target performance metric. In

22 addition, the target high/low BPI formats are designed three zones at a time and

23 the yield improvement while preserving the storage capacity is based on the

24 profile of the target nominal formats. The format optimizer 66 also allows for

25 smoothing the target variable BPI format designs. The format generator 68

26 determines the number of tracks per zone, the number of blocks per track, the

27 radius at each zone, as well as block and track format efficiency. This

28 information is saved in output files for use with the format optimizer 66. The

29 format optimizer 66 then saves the target high/low BPI formats per zone that it

30 generates in two separate files that can be loaded into the format generator 68.

31

1   Once the target format profiles are calculated, if they are non-smooth

2 across the stroke, optionally a smoothing process is applied. The format profiles

3 are then loaded into the format generator 68 to create vertically zoned formats

4 and configuration pages. The formats and configuration pages are used by the

5 disk drive firmware to create binary files to be loaded into the reserve image of

6 the disk drives as part of the file system. In this fashion, the design and

7 implementation of the format profiles as well as the number of optimal head

8 allocations are performed off-line and are predetermined for every disk drive

9 configuration.

10

11   For example, in a disk drive with four heads and four disk surfaces on two

12 disks, the format optimizer 66 designs vertically zoned high and low frequency

13 profiles. Every disk surface is uniformly partitioned into three zones across the

14 stroke, at a track density with a fixed number of tracks per zone, vertically aligned

15 from one disk surface to another. The nominal disk surface data storage before

16 the vertical zoning can be approximated by the sum over all the zones of the

17 nominal tracks per zone multiplied by the nominal BPI per track multiplied by the

18 format efficiency per zone. Format efficiency per zone is the percentage of the

19 user data that is effectively stored per zone. The nominal storage capacity is the

20 nominal disk surface data storage multiplied by the total number of disk surfaces

21 (or heads). The nominal number of tracks per zone and the format efficiency per

22 zone can be generated by the format generator 68.

23

24   Performing vertical zoning to improve the yield without losing storage

25 capacity finds the best frequency per zone and per head such that the disk drive

26 meets performance and storage capacity requirements. If a disk drive with four

27 heads fails due to the performance of head 1 at zone 1, but the performance of

28 another head/zone pair, such as head 1 at zone 2 or head 3 at zone 1, is

29 significantly better, passing the tests with reasonable margins, then a higher than

30 nominal frequency at zone 1 or zone 2 is designed for the strong heads and the

31 frequency at zone 1 for the weak head is lowered. This trade-off obtains a

1 vertically zoned design of variable frequencies per zone such that the storage

2 capacity is preserved. In addition, the number of heads per zone allocated to

3 high or low data density is determined. Thus, the storage capacity can be

4 approximated by the sum over all the zones of the number of strong heads

5 multiplied by the high frequency data storage per zone multiplied by the format

6 efficiency per zone plus the sum over all the zones of the number of weak heads

7 multiplied by the low frequency data storage per zone multiplied by the format

8 efficiency per zone.

9

10 For example, the format optimizer 66 is provided with joint BPI

11 distributions at the target performance metric. Then, for every combinatorial

12 possibility of head allocation to high or low frequency, the format optimizer 66

13 searches through a continuous range of possible frequencies by considering

14 every zone independently using the marginal distributions and by the

15 combination of zones using the joint BPI distributions to maximize the yield

16 calculated using a closed form equation, such that the storage capacity after the

17 vertical zoning is applied is essentially the same as the nominal storage capacity.

18 Further, the optimal high and low frequency profiles for every combination of

19 head allocations is compared and the one that results in the highest yield is

20 chosen and passed to the format generator 68 for the generation of vertically

21 zoned configuration pages to be used by the disk drive firmware.

22

23 The disk surfaces can be partitioned into more than three zones. To

24 reduce computational complexity and time, if the selected/designed number of

25 zones per disk surface is more than three, the format optimizer 66 can generate

26 high and low frequency profiles three zones at a time and smooth the profile after

27 post-processing. Another approach includes embedding the smoothing operator

28 in the design and extending the joint optimization to all the zones to consider the

29 impact of smoothing to yield calculation as part of the design rather than the later

30 stages.

31

1   In the disk drive with four heads, the yield is maximized while preserving

2 the nominal storage capacity. To determine the number of head allocations, the

3 format optimizer 66 begins with one weak head and three strong heads per zone.

4 The format optimizer 66 searches through a continuous range of possible

5 frequency capabilities per zone, as well as two and three zones at a time, by

6 considering the 1D, 2D and 3D BPI distributions that result in the best calculated

7 yield such that a minimum nominal storage capacity can be obtained. Next, the

8 format optimizer 66 uses two weak heads and two strong heads and repeats

9 solving the constrained optimization problem. This process is continued until all

10 the combinatorial possibilities are considered. Finally, the format optimizer 66

11 chooses the solution that results in the best yield and provides the target high

12 and low optimal data density format profiles and the associated number of high

13 and low head allocations to the format generator 68. The format generator 68

14 then generates vertically zoned format files and configuration pages to be used

15 by the disk drive firmware.

16

17 <u>Format Generator</u>

18   The format generator 68 generally performs three functions. First, the

19 format generator 68 uses target formats/frequencies (or linear densities/BPI) for

20 each zone and calculates the data storage of each zone and thus the storage

21 capacity of the disk drive. Second, the format generator 68 calculates the format

22 efficiency (the percent of the disk surface that is occupied by user data) for each

23 zone. Third, the format generator 68 generates configuration pages. The

24 configuration pages contain per-drive, per-zone, and per-head-per-zone

25 parameters that are programmed into the disk drive electronics such as the

26 preamplifier 21, the read/write channel 51 and the controller 57. The parameters

27 are ordered such that the disk drive firmware selects the correct set of

28 parameters to be programmed into each of the components for the particular

29 head and zone that is being written to or read from at the time.

30

1   The format generator 68 calculates the frequency and the data storage of

2   each zone taking into consideration limitations in the programmability and the

3   capability of the disk drive components. For example, the heads 16 have varying

4   down-track separation between the read and write elements, the preamplifier 21

5   has a minimum and maximum delay in turning on the write current, the read/write

6   channel 51 synthesizer frequencies are limited to discrete frequencies, the motor

7   driver 53 can keep the spindle motor 14 within a finite precision of the nominal

8   rotational speed, the controller 57 has specific latencies in generating commands

9   to the preamplifier 21 and the read/write channel 51 often with a finite uncertainty

10   as to the exact timing of these commands, and a reference crystal (not shown)

11   has finite accuracy and stability over temperature.

12

13   The format generator 68 can be fully automated, or can be directed by a

14   human operator. In the absence of input from the format optimizer 66, the target

15   per-zone BPI/frequency profiles, in particular, must be generated by a human

16   operator. In general, the human operator modifies the target frequency profiles

17   until the desired storage capacity is reached.

18

19   The format generator 68 includes a format efficiency process that uses the

20   format optimizer 66 target high/low variable BPI format designs as well as the

21   optimal predetermined number of high/low performing head allocations to modify

22   and generate the appropriate configuration pages as part of the file system. For

23   each zone, the format generator 68 selects the nearest frequency to the target

24   frequency for that zone, given the component limitations mentioned above. The

25   nearest frequency provides the target formats.

26

27   The optimal predetermined number of high/low performing head

28   allocations comprises the number of heads allocated to each of the multiple

29   frequencies in each zone. The format optimizer 66 determines the head

30   allocation, which is input to the format generator 68. The capacity of a zone

1　depends on the target frequencies and the number of heads allocated to each

2　frequency.

3

4　　　　The format optimizer 66 uses the nominal average BPI or frequency

5　(nominal BPI format target designs) (e.g., one read/write frequency) in each zone

6　from the format generator 68 to estimate the yield before applying the variable

7　BPI designs. For a design with multiple frequencies per zone, this is the

8　weighted average by the number of allocated heads of the multiple frequencies.

9　The nominal format is created by a human operator working with the format

10　generator 68 in an interactive manner.

11

12　　　　The format generator 68 calculates the number of tracks per zone,

13　number of blocks per track, radius at each zone as well as block and track format

14　efficiency to calculate the zone data storage. The format optimizer 66 estimates

15　the zone data storage using the tracks per zone, radii, and format efficiency.

16　Thus, the format optimizer 66 and the format generator 68 interact as shown in

17　FIG. 2A. For example, in a disk drive with four heads, and two data density

18　format frequency profiles (high and low frequency profiles) with three zones

19　across the disk surface, after the measurement and optimization processes, the

20　format generator 68 is provided with two optimal frequency profiles and the

21　optimal allocation of the heads. The format generator 68 then calculates the

22　storage capacity, and if the disk drive meets the minimum required storage

23　capacity, the format generator 68 generates the configuration pages for the disk

24　drive firmware. The configuration pages are used by the disk drive firmware to

25　command the head to write at an assigned frequency to a zone. If the calculated

26　storage capacity does not meet the minimum required storage capacity, the

27　format optimization is performed again with new format efficiency values and the

28　process is repeated.

29

30

31

1 <u>Head Assignments</u>

2   Allocating the number of heads to the predetermined multiple frequencies

3 in a zone, and assigning a particular head in a particular disk drive to a particular

4 frequency, are distinct. The allocation is performed by the format optimizer 66

5 and applies to the disk drives of a particular design. The head assignments are

6 then performed during manufacturing as part of a test process undergone by

7 each disk drive to be produced.

8   .

9   Once the configuration pages are generated and converted to binary files

10 as part of the file system, they can be loaded into a reserved image of the disk

11 drive for use after power cycling. Then, for every disk drive, the assignments are

12 performed per head and per zone to assign a predetermined number of heads to

13 high BPI formats and the remaining heads to low BPI formats in a two frequency

14 design, to satisfy the allocation of heads to the formats by the format optimizer

15 66.

16

17   The head assignments for the two frequency format where high and low

18 frequencies are used includes the steps of:

19   (1)   Load default parameters from the configuration pages, and

20 calibrate selected parameters on a per head, per zone basis (e.g., load high BPI

21 format profile for all the zones across the stroke);

22   (2)   Take measurements from the heads at the disk surfaces at

23 preselected zones with respect to a target performance metric;

24   (3)   For each head in every measured zone, sort/rank the heads by the

25 target performance metric from best to worst, select a prespecified (by the

26 allocation process in the format optimizer 66) number of heads with the best

27 performance, and assign those heads to the high frequency for a particular zone;

28   (4)   Optionally interpolate between the measurements obtained from

29 the preselected number of zones to find the results for the other zones, and do

30 the same for the interpolated zones. The interpolation reduces the test time.

31 Head performances are measured, sorted and assigned to a frequency for a

1   subset of the total number of zones. For the remaining zones, the heads are

2   assigned by interpolating the head assignments from the measurements;

3   (5)   For every zone, save the worst prespecified number of weak heads

4   with respect to the target performance metric; and

5   (6)   For every zone, load and calibrate the weak heads with the low BPI

6   format.

7

8   The above process can improve storage capacity, improve yield and

9   tradeoff between storage capacity and yield. In a test, the heads can pass or fail

10   with respect to a target performance metric to determine if the test target limits

11   are met.

12

13   The disk drive firmware is extended to load more than one format profile.

14   A head can be assigned a different read/write frequency per zone across a disk

15   surface, and radially similarly situated zones on different disk surfaces can have

16   different read/write frequencies assigned to the corresponding heads whereby

17   one head is assigned a different frequency/format profile than another head.

18

19   The head assignments apply to a format design with two recording

20   frequencies per zone, but can be easily extended to more than two frequencies

21   per zone and can be iterated to assign heads to more than two frequencies per

22   zone. For example, in a design with H heads and F frequencies per zone, steps

23   1 and 2 are completed for the high frequency. The first selection of heads in step

24   3 assigns the highest h1 heads, where h1 is the prespecified number of heads

25   allocated to the highest frequency for that zone. The remaining (H – h1) heads

26   are then loaded and calibrated with the second highest frequency (step 1 again),

27   measurements are taken (step 2 again), the heads are ordered relative to the

28   metric and the best h2 heads are assigned to the second highest frequency (step

29   3 again). Here h2 is the prespecified number of heads allocated to the second

30   highest frequency in the zone. Steps 1-3 are then iterated for the (H – h1 – h2)

31   heads, followed by the (H – h1 – h2 – h3) heads, and so on, until hF heads

33

1 remain to be assigned to the lowest frequency. The set of {h1 . . . hF} heads

2 receive the head allocation made by the format optimizer 66.

3

4   Table 1 illustrates the vertical zoning head assignments on a disk drive

5 with six heads and five zones across the stroke on each disk surface. Each head

6 is assigned to either a high or low data density format based on record/playback

7 performance of that head, and the number of heads assigned to high data

8 density and the number of heads assigned to low data density is according to the

9 head allocation determined by the format optimizer 66.

10

HEAD	ZONE 1	ZONE 2	ZONE 3	ZONE 4	ZONE 5
0	Low	High	Low	High	Low
1	High	Low	High	High	Low
2	High	Low	High	Low	High
3	High	High	Low	High	High
4	Low	High	High	High	High
5	High	High	High	Low	High

11

12 <u>Table 1</u> – Example format assignment of a disk drive after test using vertical

13 zoning with variable BPI across zones.

14

15   FIG. 3 shows a flowchart of vertical zoning data collection that includes

16 the steps of:

17   (1)   Select a number of disk drives for data measurement/collection

18 (step 300);

19   (2)   Create a nominal linear bit density profile KFCI (nominal KFCI):

20       $\overline{\text{kFCI}}(R)$, where R is the disk radius (step 302);

21   (3)   Create more linear bit density profiles by multiplying the nominal

22 KFCI by the scaling factor x_i (step 304):

$$(1 \pm x_i) * \overline{\text{kFCI}}(R)$$

23

24

25

34

1   (4)   Create a binary file system for every generated profile (step 306):

$$i \in \{1, \cdots, N\}$$

2

3   where N is the total number of frequency format profiles, for

4 example, for N = 2, having X_1, and X_2, if $X_1 = 0.05$ and $X_2 = 0.1$, then including

5 the nominal frequency format there are five different frequency profiles in step

6 304 as follows: (a) nominal KFCI, (b) 1.05 x nominal KFCI, (c) 0.95 x nominal

7 KFCI, (d) 1.1 x nominal KFCI, and (e) 0.90 x nominal KFCI;

8   (5)   Select the first head by setting i to 1(step 308);

9   (6)   Load the file system i into the reserved image of the disk drives

10 (step 310);

11   (7)   Take the head performance measurements (step 312);

12   (8)   Unload and save the results in the data base (step 314);

13   (9)   Increment i by one (step 316);

14   (10)   Determine if i = N (step 318);

15   (11)   If not, go to step 310; and

16   (12)   Otherwise, stop (step 320).

17

18   The above process collects performance data for all the heads at all the

19 zones.

20

21   FIG. 4 shows a flowchart of vertical zoning post-measurement and per

22 zone BPI distribution extraction that includes the steps of:

23   (1)   Organize the head performance data for every head $i \in \{1, \cdots, M_1\}$

24 and every zone $j \in \{1, \cdots, M_2\}$ as a function of the linear bit density samples,

25 where M_1 is the total number of heads in the disk drives selected for

26 measurement and M_2 is the total number of zones, to generate head

27 performance histograms (step 400);

28   (2)   Choose a target performance metric (step 402);

29   (3)   Set $j = 1$ and $i = 1$ (step 404);

1   (4)   Interpolate/extrapolate BPI at the target performance metric for

2   head i at zone j (step 406);

3   (5)   Select the next head by incrementing i by one (step 408);

4   (6)   Determine if all the heads have been processed by determining if

5    $i = M_1$ (step 410);

6   (7)   If not, go to step 406 to process the next head, otherwise generate

7   a frequency capability histogram at zone j for all the heads (step 412);

8   (8)   Determine if all the zones have been processed by determining if

9    $j = M_2$ (step 414);

10   (9)   If not, move to the next zone and start with the first head again, set

11   $j = j + 1$ and $i = 1$ (step 416) and go to step 406; and

12   (10)   Otherwise, stop (step 418).

13

14   The above process generates 1D frequency capability histograms at a

15   target performance metric for every zone by considering all the heads from the

16   sample disk drives selected for measurement. Using the 1D frequency capability

17   histograms at a target performance metric, probability theory known to those

18   skilled in the art can be adopted to estimate the 1D frequency capability

19   distributions. Further, the above process is extended by using 2D and 3D

20   interpolation/extrapolation routines to extract and estimate the 2D and 3D joint

21   frequency capability histograms and their associated distributions.

22

23   FIG. 5 shows a flowchart of head assignments for N heads with a two

24   frequency format (high/low data density) that includes the steps of:

25   (1)   Assign all the heads in a disk drive to the high data density format

26   (step 500);

27   (2)   Calibrate all the heads at the high data density format for selected

28   zones (step 502);

29   (3)   Measure the head performance metric at the selected zones for all

30   the heads (step 504);

1   (4)   For each selected zone, rank the heads by the head performance

2 metric (step 506);

3   (5)   For each selected zone, assign the highest K heads to the high

4 data density format, and assign the other N-K heads to the low data density

5 format (step 508);

6   (6)   Optionally interpolate the head assignments for the remaining

7 zones (step 510); and

8   (7)   Complete the calibration of all the heads and all the zones at the

9 assigned formats (step 512).

10

11   The above process completes the assignment of each head in each disk

12 drive to a predetermined frequency.

13

14   The format generator 68 passes the track formats to the format optimizer

15 66 to have a more accurate way of calculating the storage capacity (nominal

16 format). Such information and constraints are provided to the format optimizer

17 66 to solve the joint optimization problems. The format optimizer 66 performs a

18 coarse calculation of the storage capacity, whereas the format generator 68

19 performs an exact calculation of the storage capacity. The format generator 68

20 provides format information (such as number of tracks per zone, and the zone

21 format) to the format optimizer 66, and calculates the exact storage capacity.

22 Such information is passed once from the format generator 68 to the format

23 optimizer 66 for a head design with a given number of heads. The format

24 generator 68 initially provides nominal information to the format optimizer 66, and

25 the format optimizer 66 performs its calculation of target densities (zone

26 frequencies and number of heads allocated to each frequency) and provides that

27 information to the format generator 68. The format generator 68 then determines

28 if required storage capacity has been reached. Adjusting the target densities to

29 meet storage capacity and/or yield requirements includes adjusting the selected

30 zone density or zone frequencies.

31

1   FIG. 6 shows a flowchart of format generation and optimization in which

2   an iterative process for a minimum storage capacity (C) and a user specified

3   storage overcapacity (Δ) includes the steps of:

4   (1)   Determine the disk geometry, track density and servo spoke

5   details, and provide the inner diameter (ID) and outer diameter (OD) radii, the

6   track density (TPI), the number of servo spokes, and the servo spoke length

7   (step 600);

8   (2)   The format generator 68 generates the initial format at the storage

9   capacity using the ID and OD radii, the TPI, the number of servo spokes and the

10   servo spoke length, and provides the radius of each zone per disk surface, the

11   number of tracks per zone, the number of blocks per track, and the format

12   efficiency by zone (step 602);

13   (3)   The format optimizer 66 generates optimal target densities at all the

14   zones using the radius of each zone per disk surface, the number of tracks per

15   zone, the number of blocks per track, and the format efficiency by zone and

16   provides the high and low BPI targets by zone and the number of high and low

17   BPI head allocations by zone (step 604);

18   (4)   The format generator 68 generates new formats with a storage

19   capacity (the number of logical blocks per disk drive) (step 606);

20   (5)   Determine if the storage capacity > C and the storage capacity < (C

21   + Δ) (step 608);

22   (6)   If not, adjust the target densities (step 610) and go to step 606; and

23   (7)   Otherwise, stop (step 612).

24

25   For example, the disk surface capacity is TPI x BPI x (1 + ECC) / FE,

26   where TPI is the track density, BPI is the linear bit density, ECC is the fractional

27   level of error correcting code which is typically about 0.1, and FE is the format

28   efficiency which is typically about 0.57.

29

30   The above process completes the format generation.

31

1   As another example, a set of thirty-two mature disk drives are selected

2   and each disk drive includes twelve heads. The 1D, 2D and 3D BPI distributions

3   are extracted at an on-track symbol error rate from the outer, middle and inner

4   zones. Next, the BPI distributions are fed to the format optimizer 66, and high or

5   low frequency per zone format designs are obtained at the three zones. This is

6   performed once by individual optimization based on 1D BPI distributions at each

7   of the three zones, and once by joint optimization based on the measurements

8   obtained from the three zones and their extracted 1D, 2D and 3D BPI

9   distributions. The head format allocation search is performed by simulation, and

10   for each zone the one-format designs before the application of vertical zoning are

11   a special case of the two-format variable BPI designs by forcing the high and low

12   formats to be equal to the nominal BPI format at that zone. Furthermore, the

13   pass/fail of the disk drives is based on each head at every zone passing a target

14   on-track symbol error rate as well as off-track squeeze and unsqueeze offset

15   margins. Then, the yield is calculated by simulation by interpolation/extrapolation

16   of the measurement data before and after the application of vertical zoning (VZ).

17   Table 2 summarizes the results:

	Using Joint Optimization	Using Individual Optimization
Drive Yield (Yd)	93.75	90.625
Drives failed after VZ	4 & 29	4, 6 & 29
Drives recovered	2, 3, 13, 19, 21 & 25	2, 3, 13, 19, 21 & 25
Passed drives failed after VZ	None	6
Drives failed before VZ	2, 3, 4, 12, 19, 21 & 29	2, 3, 4, 12, 19, 21 & 29
	i.e., drive yield before VZ	i.e., drive yield after VZ
	Yd=75%	Yd = 75%

<u>Table 2</u>

31   Although a manufacturing test case for a two format design is illustrated,

32   the search algorithm can be easily generalized to a higher number of formats.

33   The design of two formats based on 1D, 2D and 3D BPI distributions can easily

34   be generalized to higher order or dimensions by considering more than three

35   zones. The format design can be generalized from two to a higher number of

36   formats. The measurement procedure can be generalized to consider more

37   zones as well as off-track measurements such as 747 curves or quality metrics

1   versus error rate measurements to perform a correlation study for the best metric

2   with the least test time.

3

4   Further, the per zone variable BPI design can be easily extended to a

5   variable BPI/TPI design. The measurement process is extended to include 747

6   measurements of all the heads from a preselected number of disk drives. To

7   speed up the measurements, instead of 747 measurements, off-track and

8   adjacency margin squeeze measurements of the heads can be performed. Once

9   the 747 data of the heads at a preselected number of zones is determined, for

10 every zone, joint BPI/TPI distributions can be extracted at the target(s) by post-

11 measurement data processing. The choice of a target is an integral part of the

12 performance gain, such as yield, due to the per zone variable BPI/TPI designs.

13 Some example targets are off-track symbol error rate, position error signal

14 variance, and a combination of both. After the joint BPI/TPI distributions are

15 extracted and available for the zones, a per zone variable BPI/TPI design can be

16 obtained by solving two constrained (joint) optimization problems: one that

17 maximizes the yield while keeping the same disk drive areal density, and another

18 that maximizes the disk drive areal density while keeping the same yield. Once

19 the per zone variable BPI/TPI designs are obtained, a preselected number of

20 heads are allocated to high and low density BPI and TPI formats, for example, for

21 a two variable BPI/TPI per zone design performed as part of the test process.

22

23 The present invention improves storage capacity (and consequently areal

24 density at a fixed target BPI) and yield and reduces the target TPI by increasing

25 the average BPI across the stroke per head (depending on the number of

26 formats considered) to meet a desire storage capacity. In particular, the BPI at

27 the outer diameter may be limited by the maximum deliverable data rate of the

28 ASIC components. For example, if the controller 57 has a maximum deliverable

29 data rate of 650 MHz, the preamplifier 21 has a maximum deliverable data rate of

30 700 MHz and the read/write channel 51 has a maximum deliverable data rate of

31 750 MHz, then the BPI at the outer diameter is limited by the controller 57 at a

1 maximum deliverable data rate of 650 MHz. Thus, a conventional one format

2 BPI profile across the stroke does not achieve the desired storage capacity and

3 yield, whereas the present invention per zone variable BPI target formats meet

4 the desired storage capacity at a fixed target TPI while improving the yield.

5

6 The data measurer 62 can be implemented by a general purpose

7 computer 61 and the drive electronics of the disk drive 100. The general purpose

8 computer 61 can be a high end PC, a PC server or a workstation and include

9 programmable simulation software. The drive electronics can include the logic

10 circuit 49 and the controller 57. The logic circuit 49 performs the measurements

11 and the controller 57 directs the logic circuit 49 and transfers the data to the

12 general purpose computer 61. The head assignments can be implemented by

13 the controller 57 with the data collection sub-task performed by the logic circuit

14 49. The post-measurement data processor 64, the format optimizer 66 and the

15 format generator 68 can be implemented by the general purpose computer 61.

16

17 The present invention has been described in considerable detail with

18 reference to certain preferred versions thereof; however, other versions are

19 possible. Therefore, the spirit and scope of the appended claims should not be

20 limited to the description of the preferred versions contained herein.

1 **<u>Abstract</u>**

2   A method of defining a storage format in data storage devices, each data

3 storage device having multiple storage media and corresponding heads, each

4 head for recording on and playback of information from a corresponding storage

5 media in at least one zone, and each zone including concentric tracks for

6 recording on and playback of information. The method includes selecting a

7 sample of the data storage devices, for each selected data storage device

8 measuring a record/playback performance capability of each head at one or

9 more read/write frequencies per zone, generating storage density distributions

10 corresponding to the heads in the selected data storage devices based on the

11 performance capability measurements, selecting a group of read/write

12 frequencies for the data storage devices with two or more frequencies for each

13 zone based on the storage density distributions, and assigning one of the

14 read/write frequencies to each head based on the performance capability of that

15 head.

FIG. 1A

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Filed: 01/26/2002   Reply Mailed: August 15, 2005
Docket No.: Q01-1006-US1   Confirmation No. 4114
Inventor: ASGARI et al.   Group Art Unit: 2651
Attorney: Tejpal S. Hansra   Telephone: 360-527-1400

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FIG. 1B

	Se ~37~	Tk3 ~35~
	Sd ~37~	
	Sc ~37~	Tk2
	Sb ~37~	Tk1
	Sa ~37~	

FIG. 1C

FIG. 1D

60

12

60

60

Disk 1

Disk 2

Disk N

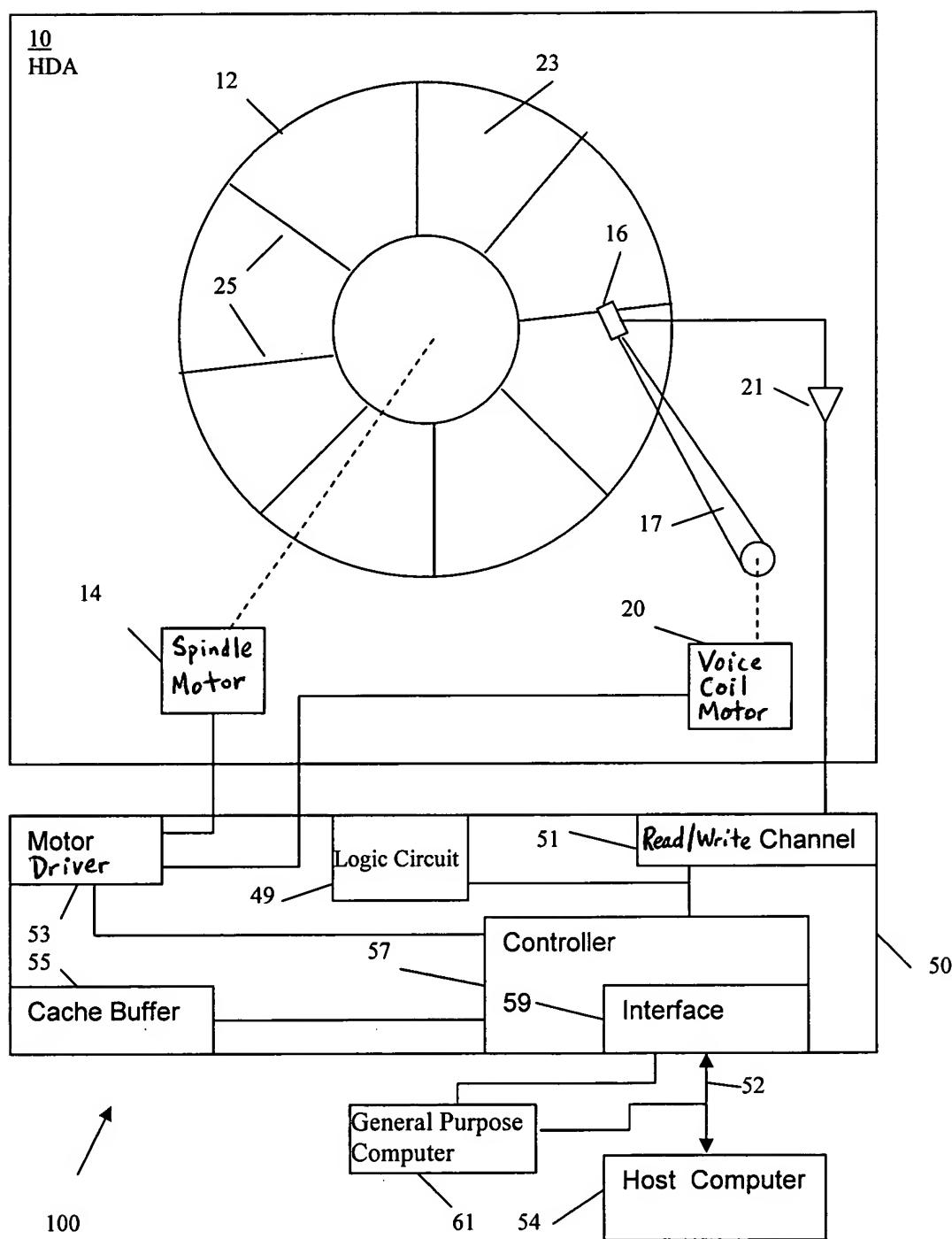Head 1, Zone 1
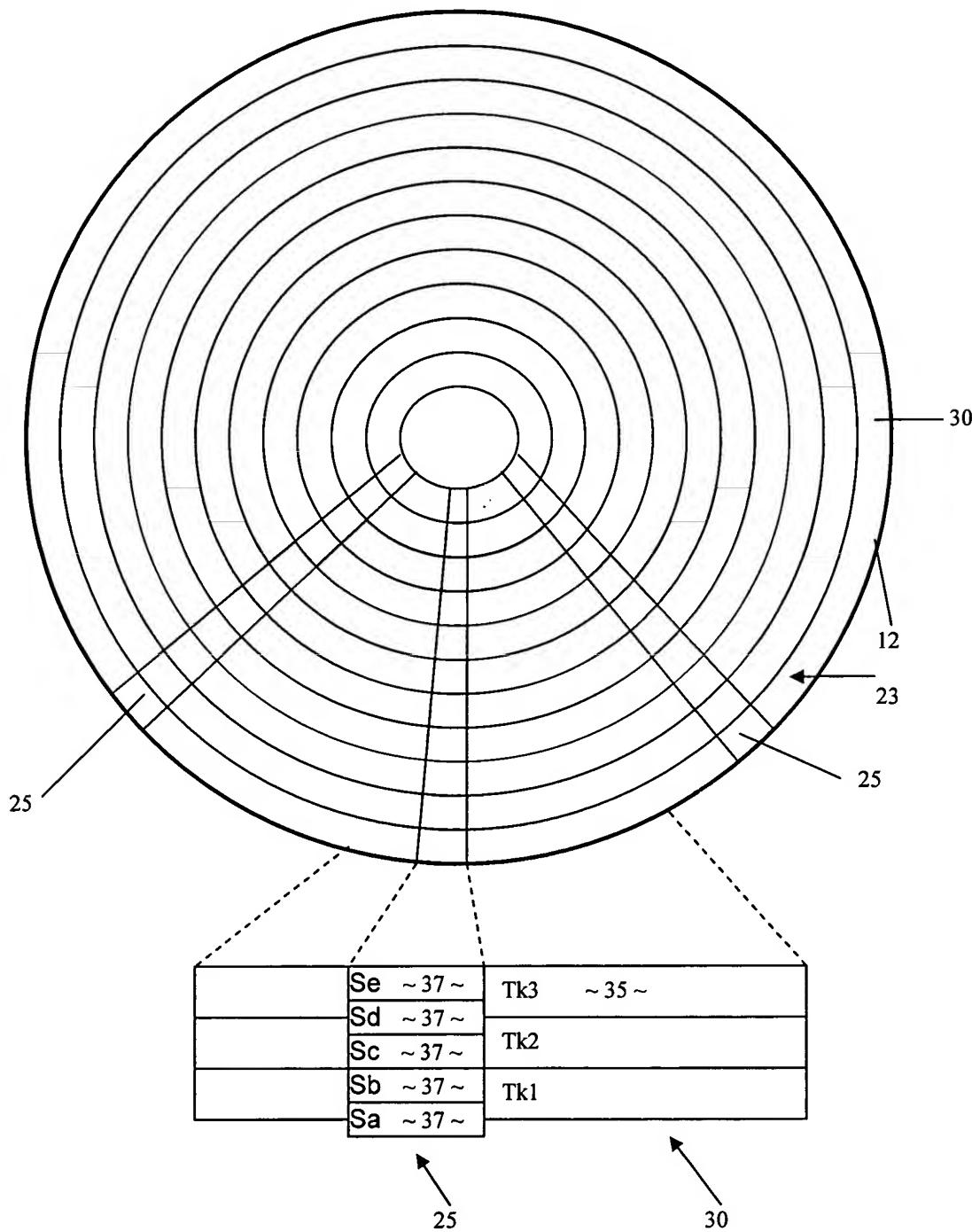Format

Head 3, Zone 1
Format

Head 2N-1, Zone 1
Format

FIG. 1E

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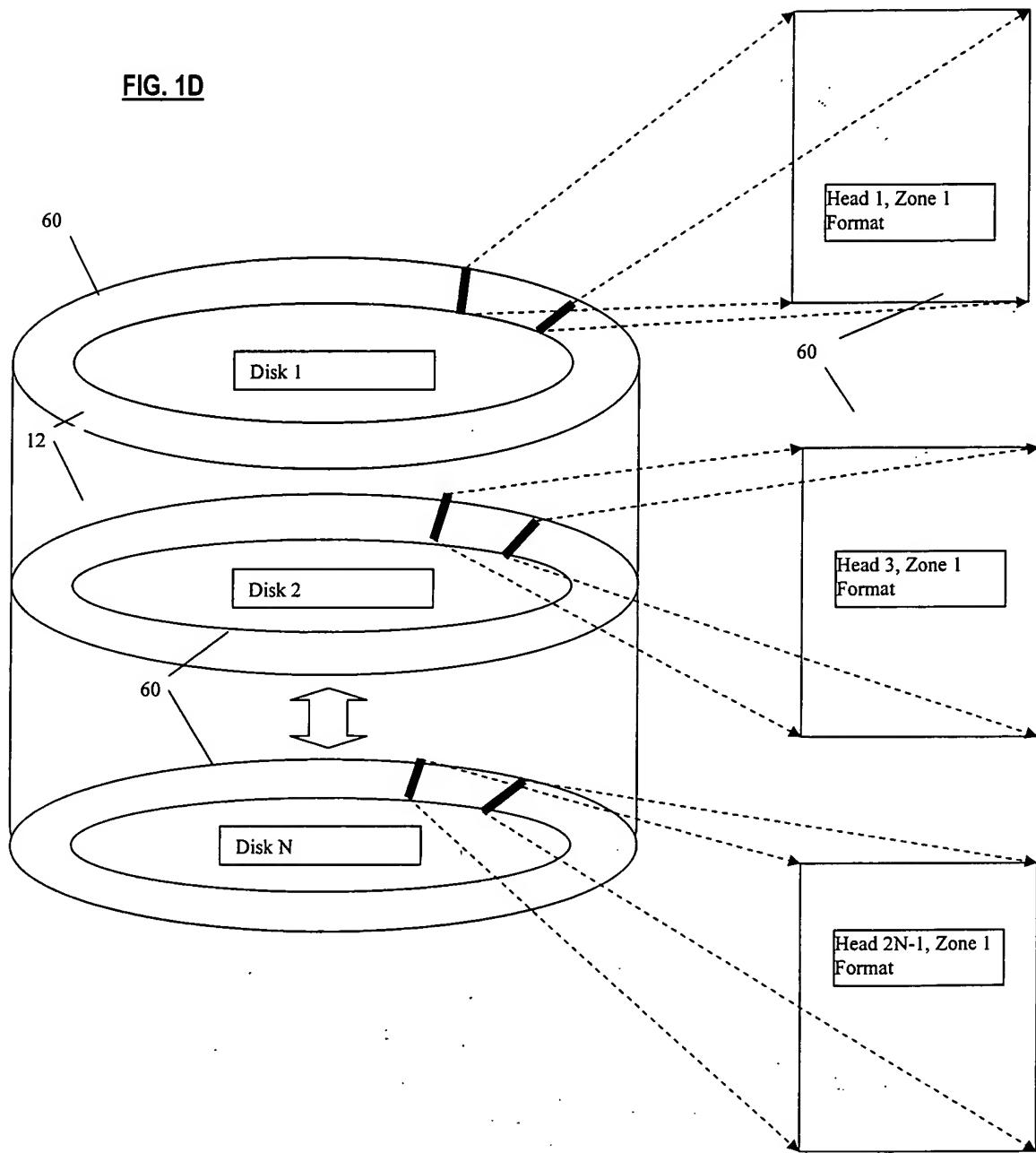Telephone: 360-527-1400

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60 (Zone M)
Virtual Cylinder l ... Virtual Cylinder i
39   39

60 (Zone 1)
Virtual Cylinder l ... Virtual
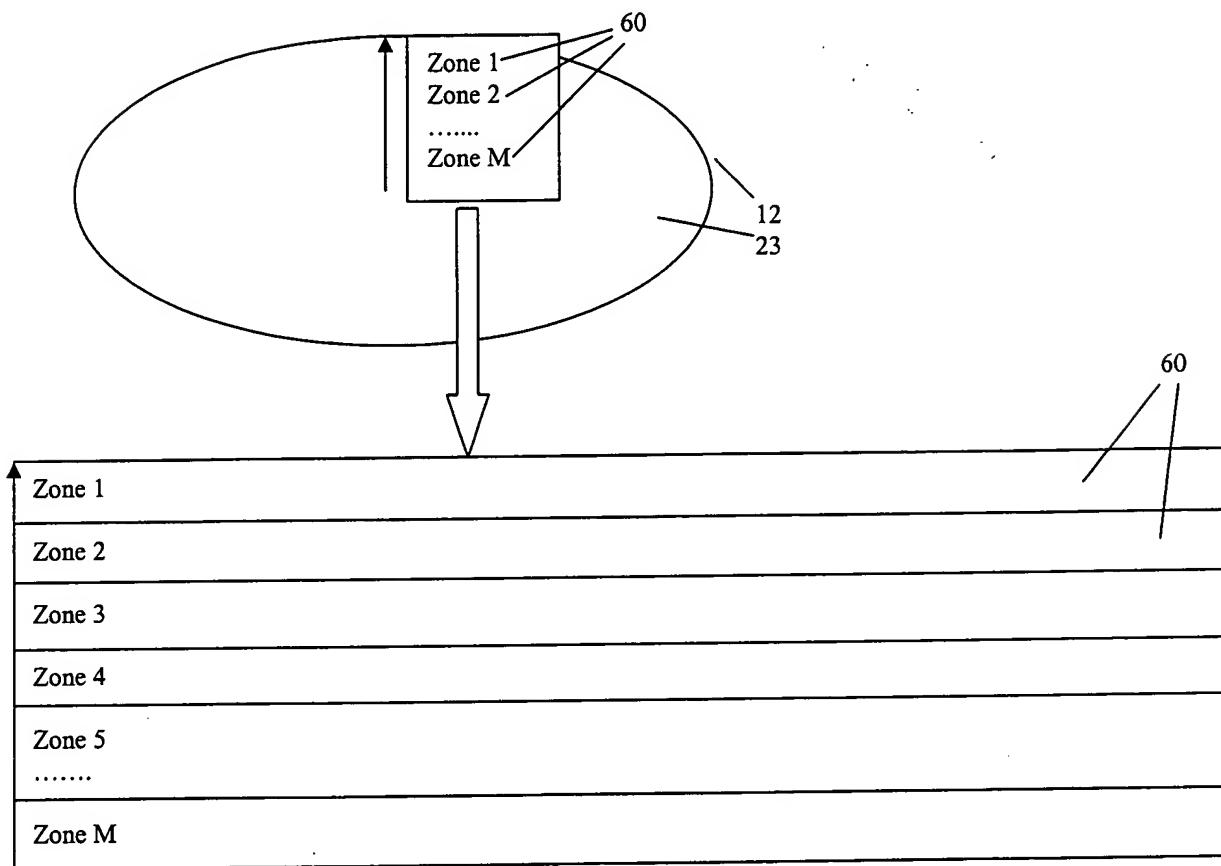39   39   Cylinder j

FIG. 1F

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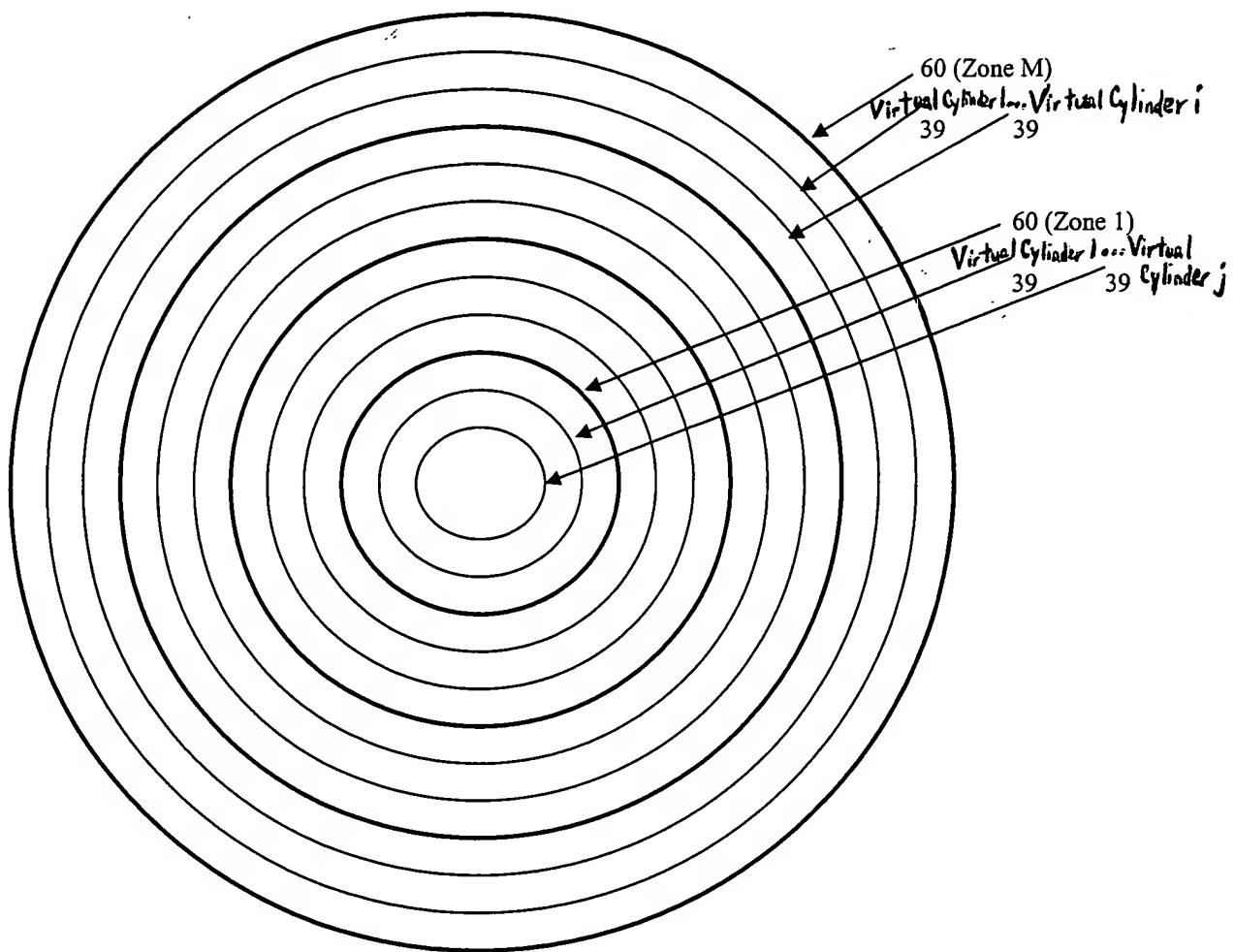
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FIG. 1G

Head 1

Virtual Cylinder 1 Track 0
Virtual Cylinder 1 Track 1
Virtual Cylinder 1 Track 2
Virtual Cylinder 1 Track 3
Virtual Cylinder 1 Track 4
Virtual Cylinder 2 Track 0
Virtual Cylinder 2 Track 1
Virtual Cylinder 2 Track 2
Virtual Cylinder 2 Track 3
Virtual Cylinder 2 Track 4
Virtual Cylinder 3 Track 0
Virtual Cylinder 3 Track 1
Virtual Cylinder 3 Track 2
Virtual Cylinder 3 Track 3
Virtual Cylinder 3 Track 4

Head 2

39

Virtual Cylinder 1 Track 0
Virtual Cylinder 1 Track 1
Virtual Cylinder 1 Track 2
Virtual Cylinder 1 Track 3
Virtual Cylinder 1 Track 4
Virtual Cylinder 2 Track 0
Virtual Cylinder 2 Track 1
Virtual Cylinder 2 Track 2
Virtual Cylinder 2 Track 3
Virtual Cylinder 2 Track 4
Virtual Cylinder 3 Track 0
Virtual Cylinder 3 Track 1
Virtual Cylinder 3 Track 2
Virtual Cylinder 3 Track 3
Virtual Cylinder 3 Track 4

35

60

Head N

Virtual Cylinder 1 Track 0
Virtual Cylinder 1 Track 1
Virtual Cylinder 1 Track 2
Virtual Cylinder 1 Track 3
Virtual Cylinder 1 Track 4
Virtual Cylinder 2 Track 0
Virtual Cylinder 2 Track 1
Virtual Cylinder 2 Track 2
Virtual Cylinder 2 Track 3
Virtual Cylinder 2 Track 4
Virtual Cylinder 3 Track 0
Virtual Cylinder 3 Track 1
Virtual Cylinder 3 Track 2
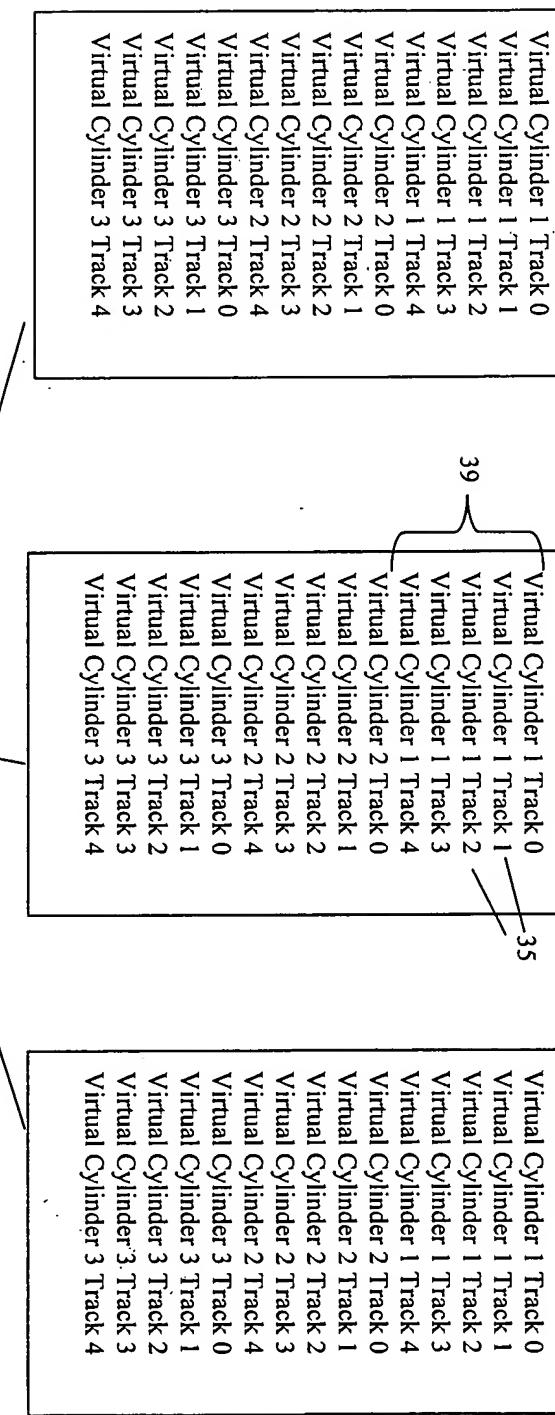Virtual Cylinder 3 Track 3
Virtual Cylinder 3 Track 4

FIG. 1H   37 30   Head 1   Head 2

VIRTUAL CYLINDER 1		Head 1	Head 2
	Servo Track 0	Data Track 0	Data Track 0
	Servo Track 1		
	Servo Track 2	Data Track 1	Data Track 1
	Servo Track 3	Data Track 2	Data Track 2
	Servo Track 4		
	Servo Track 5	Data Track 3	Data Track 3
	Servo Track 6	Data Track 4	Data Track 4
	Servo Track 7		
		Data Track 5	Data Track 5
39	Servo Track 8		
VIRTUAL CYLINDER 2	Servo Track 9	Data Track 6	Data Track 6
	Servo Track 10		
	Servo Track 11	Data Track 7	Data Track 7

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Head 1, Zone 1 Format Layout   37 30

Servo Track 0

Data Track 0

Servo Track 1

Data Track 1

Servo Track 2

Servo Track 3

Data Track 2

Servo Track 4

Data Track 3

Servo Track 5

60

Head 1, Zone M Format Layout   37 30

Servo Track 0

Data Track 0

Servo Track 1

Servo Track 2

Data Track 1

Servo Track 3

Servo Track 4

Data Track 2

Servo Track 5

Servo Track 6

Data Track 3

Servo Track 7

60

FIG. 11

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FIG. 2A

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+ — Frequency sample
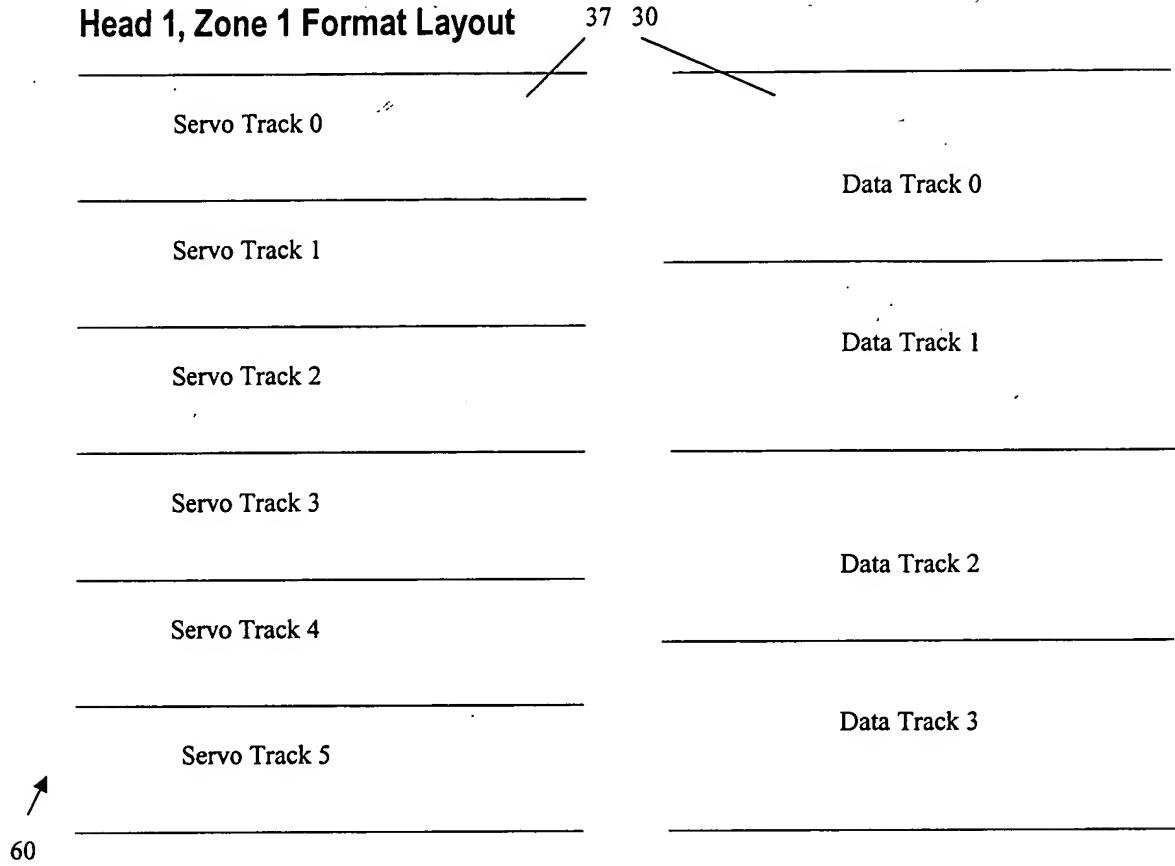O — Least square polynomial fit
◇ — Projected frequency

FIG. 2B

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Inventor: ASGARI et al.
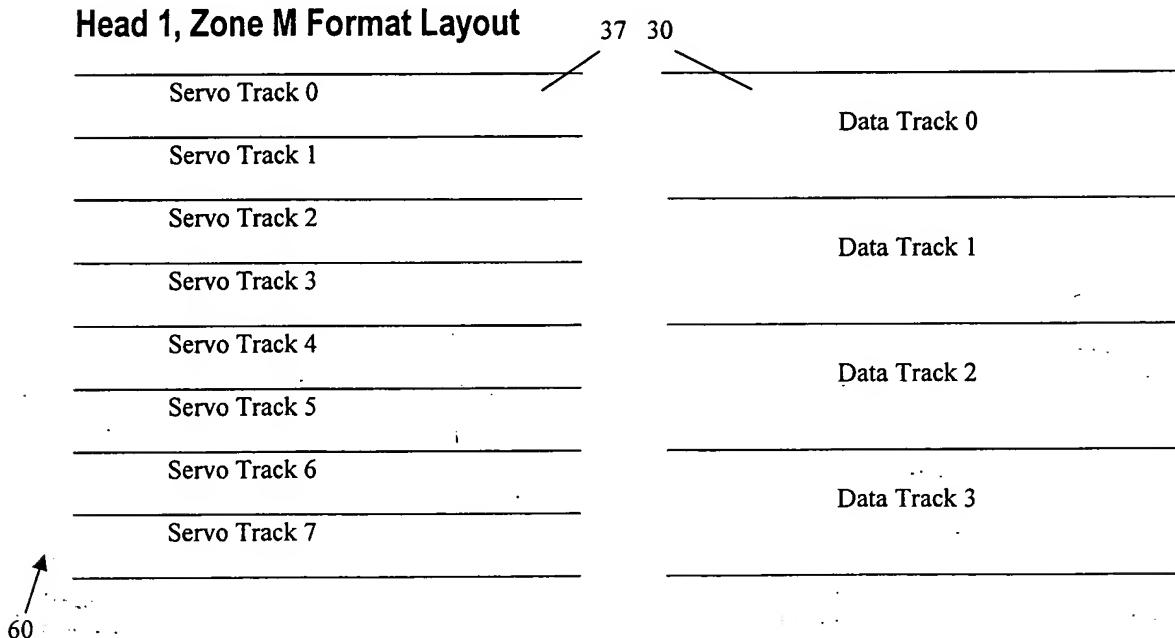Attorney: Tejpal S. Hansra

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FIG. 2C

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Attorney: Tejpal S. Hansra   Telephone: 360-527-1400

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BPI at outer diameter   BPI at middle diameter

FIG. 2D

Select appropriate disk drives — 300

302 — Create nominal linear bit density profile $\overline{kFCI}(R)$ (R= radius)

Create more linear bit density profiles $(1 \pm x_i) * \overline{kFCI}(R)$

Create binary file system for every generated profile for $i \in \{1, \cdots, N\}$

304

306

Let $i = 1$

308

Load file system i into reserved image of disk drives

310

Take head performance measurements

312

$i = i + 1$

316

Unload and save results in data base

314

Is $i = N$?

No

Yes

Stop — 320

318

FIG. 3

Organize the performance data for every head $i \in \{1, \cdots, M_1\}$ and every zone $j \in \{1, \cdots, M_2\}$ as a function of linear bit density samples

400

Choose a target performance metric

402

Let $j = 1$ and $i = 1$

404

410

408

406

No

Is $i = M_1$?

$i = i + 1$

Interpolate/Extrapolate BPI at target performance metric for head i at zone j

Yes

Generate frequency capability histogram at zone j for all heads

412

414

416

Is $j = M_2$?

No

$j = j + 1$ and $i = 1$

Yes

418

Stop

FIG. 4

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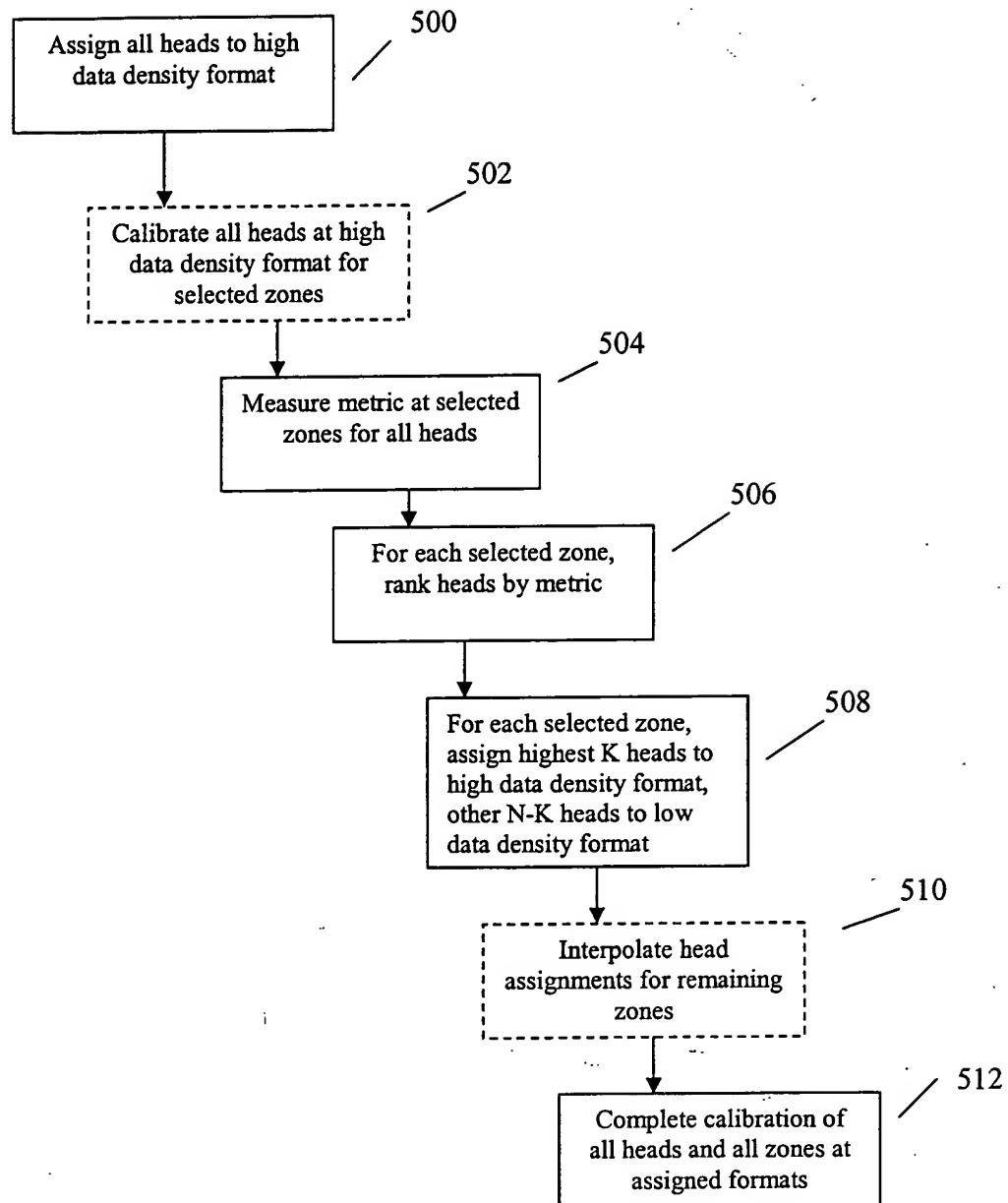
```
        ┌─────────────────────┐  ╱ 500
        │  Assign all heads to │ ╱
        │  high data density   │
        │  format              │
        └──────────┬──────────┘
                   │
                   ▼
        ┌ ─ ─ ─ ─ ─ ─ ─ ─ ─ ─ ┐  ╱ 502
          Calibrate all heads at  ╱
        │ high data density     │
          format for
        │ selected zones        │
        └ ─ ─ ─ ─ ─┬─ ─ ─ ─ ─ ─ ┘
                   │
                   ▼
        ┌─────────────────────┐  ╱ 504
        │  Measure metric at   │ ╱
        │  selected zones for  │
        │  all heads           │
        └──────────┬──────────┘
                   │
                   ▼
        ┌─────────────────────┐  ╱ 506
        │  For each selected   │ ╱
        │  zone, rank heads by │
        │  metric              │
        └──────────┬──────────┘
                   │
                   ▼
        ┌─────────────────────┐  ╱ 508
        │  For each selected   │ ╱
        │  zone, assign        │
        │  highest K heads to  │
        │  high data density   │
        │  format, other N-K   │
        │  heads to low data   │
        │  density format      │
        └──────────┬──────────┘
                   │
                   ▼
        ┌ ─ ─ ─ ─ ─ ─ ─ ─ ─ ─ ┐  ╱ 510
          Interpolate head       ╱
        │ assignments for       │
          remaining zones
        └ ─ ─ ─ ─ ─┬─ ─ ─ ─ ─ ─ ┘
                   │
                   ▼
        ┌─────────────────────┐  ╱ 512
        │  Complete            │ ╱
        │  calibration of all  │
        │  heads and all zones │
        │  at assigned formats │
        └─────────────────────┘
```

FIG. 5

FIG. 6